Microelectromechanical Systems Opportunities

A Department of Defense Dual-Use Technology Industrial Assessment

Introduction

As military information systems increasingly leave command centers and appear in weapons systems and in the pockets and palms of combatants, they are getting closer to the physical world, creating new opportunities for perceiving and controlling the battlefield environment. To exploit these opportunities, information systems will need to *sense* and *act* as well as *compute*. Filling this need is the driving force for the development of microelectromechanical systems (MEMS).

Using the fabrication techniques and materials of microelectronics as a basis, MEMS processes construct both *mechanical* and electrical components. Mechanical components in MEMS, like transistors in microelectronics, have dimensions that are measured in microns and numbers measured from a few to millions. MEMS is not about any one single application or device, nor is it defined by a single fabrication process or limited to a few materials. More than anything else, MEMS is a fabrication approach that conveys the advantages of miniaturization, multiple components and microelectronics to the design and construction of integrated *electromechanical* systems.

MEMS devices are and will be used widely, with applications ranging from automobiles and fighter aircraft to printers and munitions. While MEMS devices will be a relatively small fraction of the cost, size and weight of these systems, MEMS will be critical to their operation, reliability and affordability. MEMS devices, and the smart products they enable, will increasingly be the performance differentiator for both defense and commercial systems.

This report identifies candidate MEMS defense applications, assesses the global MEMS industry, summarizes the level of global investments in MEMS, and outlines a DoD investment strategy and action plan for MEMS.

Defense Applications of MEMS

Experiences in recent conflicts and the evolving role of the US military stressing rapid response to varying missions have demonstrated the compelling advantage of securing accurate and timely information. Coupled with smart weapons systems, the resulting combination of awareness and lethality will be key to increasing and projecting military capability in the 21st century. MEMS embedded into weapons systems, ranging from competent munitions and sensor networks to high-maneuverability aircraft and identify-friend-or-foe systems, will bring to the military new levels of situational awareness, information to the warrior, precision strike capability, and weapons performance/reliability. These heightened capabilities will translate directly into tactical and strategic military advantage, saved lives, and reduced material loss.

MEMS will create new military capabilities, make high-end functionality affordable to low-end military systems, and extend the operational performance and lifetimes of existing weapons platforms. For example, MEMS will enable complete inertial navigation units on a chip, composed of multiple integrated MEMS accelerometers and gyroscopes. The inertial navigation systems of today, however, are large, heavy, expensive, power-consumptive, precision instruments affordable only in high-end weapons systems and platforms. Inertial navigation on a chip would not only make it possible to augment global positioning satellite receivers for battlefield tracking of troops and equipment, but would also provide guidance for high-volume munitions that are currently unguided. MEMS inertial navigation units on a chip will achieve performance comparable to or better than existing inertial navigation systems and be no larger, costlier, or more power consumptive than microelectronic chips.

In addition to single-chip inertial navigation units, there are many opportunities for MEMS insertion into DoD systems across a number of technologies and products that include

- *distributed unattended sensors* for asset tracking, border control, environmental monitoring, security surveillance and process control,
- *integrated fluidic systems* for miniature chemical/biological analysis instruments, hydraulic and pneumatic systems, propellant and combustion control, and printing technology,
- *weapons safing, arming and fuzing* to replace current warhead systems to improve safety and reliability,
- *low-power, high-resolution, small-area displays* for tactical and personal information systems,
- *embedded sensors and actuators* for condition-based maintenance of machines and vehicles, on-demand amplified structural strength in lower-weight weapons systems/platforms and disaster-resistant building,
- *mass data storage devices* for storage densities of terabytes per square centimeter,

- *integrated microoptomechanical components* for identify-friend-or-foe systems, displays and fiber-optic switches/modulators, and
- *active, conformal surfaces* for distributed aerodynamic control of aircraft, adaptive optics, and precision parts and material handling.

Some early MEMS device concepts have either been demonstrated or are in commercial production. These devices include a projection display system with a MEMS chip that is an array (about the size of a large postage stamp) of over a million individual micromirrors producing a high-resolution video image; a flow regulator the size a pencil eraser capable of operating at air pressures of up to 3000 pounds per square inch; and a single-axis, 50-G accelerometer for air-bag deployment. The MEMS air-bag deployment sensor is not only smaller, lighter, cheaper, more reliable, and has higher performance than the present sensor, it also is being built in an integrated circuit fabrication line of a major US microelectronics manufacturer like other types of semiconductor chips produced.

To realize many of the devices and systems envisioned for MEMS defense application, advances in present capabilities are needed to take MEMS technology to the higher performance levels required for DoD applications. For example, the sensitivities and stabilities required for inertial navigation on a chip have to be three to four orders of magnitude better than the best MEMS accelerometers or gyroscopes available today. Since current inertial sensing device performance is more than adequate to meet the anticipated needs of automotive markets (the primary non-defense market for inertial sensors), the commercial sector alone will not drive the development of the MEMS technology to the densities of integrated electronics and mechanics needed for inertial navigation on a chip (see Figure 20 in Appendix).

To realize the devices and systems in other MEMS defense applications, including munitions safing & arming and condition-based maintenance, existing or near-term commercial MEMS technologies and products need to be adapted and qualified for military use. For example, signal detection and processing requirements are likely to vary, which will mean different co-fabricated electronics designs and changes in the ways signals are detected (e.g., different ranges or thresholds). Once modified, laboratory and field tests for specific applications at extreme conditions (e.g., shock and temperature) will also be needed to ensure suitability for DoD needs.

For yet other applications such as MEMS devices operating in high-temperature conditions for combustion control, new materials and process developments will be required. For example, because devices made of silicon cannot be used at temperatures above 150° C, such devices cannot be used directly inside of engines. MEMS devices in new materials such as silicon carbide, however, will enable operation at temperatures nearly three times present limits. In all application areas, because MEMS is a growing and emerging industry, DoD needs, products and investments can be aligned with those of the commercial sector early in the establishment of the technology, ensuring a national and integrated defense-commercial MEMS industry.

Defense applications for MEMS have been identified in three major areas: inertial measurement (weapon safing, arming and fuzing, competent munitions, platform stabilization, personal/vehicle navigation, and condition-based maintenance), distributed sensing and control (condition-based maintenance, situational awareness, miniature analytical instruments, identify-friend-or-foe systems, biomedical sensors, and active structures), and information technology (mass data storage and displays). For each MEMS defense application area identified, there is a brief description of the application, the military justification for the desired capability, the principal benefits of a MEMS insertion, the estimated DoD market, and technology adoption issues or hurdles. Figure 1 summarizes the present level of MEMS funding, insertion activities and technology maturity of the twelve major, identified MEMS defense applications:

	MEMS Application	Current DoD Technology Funding	Current DoD Insertion Activities	Technical Maturity
Inertial Measurement Applications	Weapon Safing, Arming & Fuzing	◒	◒	◒
	Competent Munitions	◒	○	●
	Platform Stabilization	○	○	◒
	Personal/Vehicle Navigation	○	○	○
Distributed Sensing and Control Applications	Condition-Based Maintenance	○	○	●
	Situational Awareness	◒	○	◒
	Miniature Analytical Instruments	○	○	○
	Identify-Friend-or-Foe	—	—	○
	Biomedical Devices	◒	◒	◒
	Active Structures	○	—	○
Information Technology Applications	Mass Data Storage	○	—	○
	Displays	●	◒	◒

Key

- ● strong
- ◒ modest
- ○ weak
- — none

FIGURE 1. MEMS technical funding and insertion status summary chart. DoD applications are broadly categorized in the areas of inertial measurement, distributed sensing and control, and information technology.

A. Inertial Measurement

The worldwide MEMS inertial sensing market is presented in Figure 2. Although military requirements represent a fraction of the projected total inertial sensing market, the DoD will be an early user of and driver for high-performance MEMS inertial measurement products. Key DoD inertial measurement applications identified are weapons safing, arming and fuzing, competent munitions, platform stabilization, and personal/vehicle navigation.

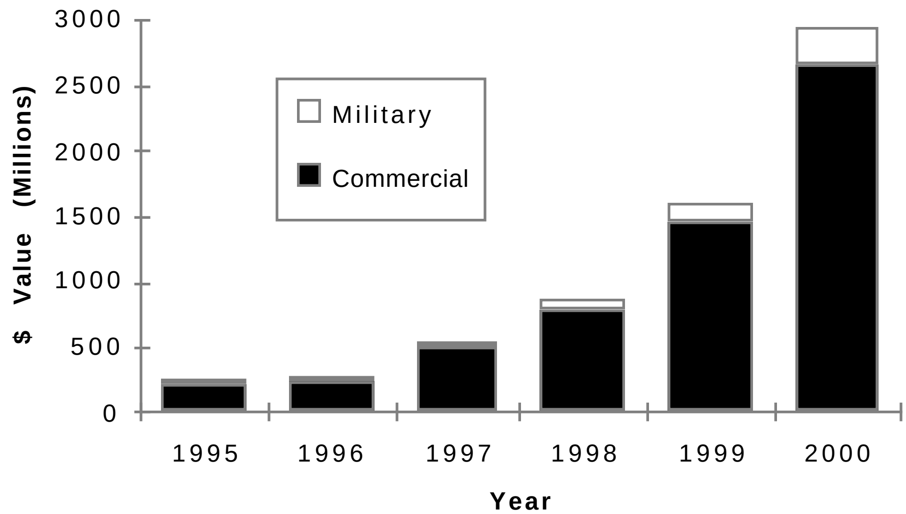


FIGURE 2. Worldwide MEMS inertial sensing products market.

1. Weapon Safing, Arming, and Fuzing

Replace explosive warhead fuzing and safe-arming devices with MEMS devices to improve their operation, safety, and reliability.

Historical data and the recent combat actions in Desert Storm and U.N. actions in Bosnia continue to demonstrate that a significant percentage of U.S. ordnance fails to detonate as intended. Unexploded ordnance (UXO) reduces the effectiveness of military operations, erodes the confidence and morale of soldiers, and presents a significant threat to the safety of civilians and combatants during and after a conflict.

When ordnance fails to detonate as planned, additional sorties and munitions are needed to finish the job, or the intended targets are not destroyed.

Having to re-attack previous targets strains logistics supply lines and increases the risks of casualties and materiel losses. During Desert Storm there were 94 incidents where UXO caused casualties on friendly forces, resulting in 104 injuries and 30 deaths. After a conflict, UXO also requires a costly, intensive explosive ordnance disposal (EOD) effort to clear the former battlefield and make it safe for civilians. Based on information supplied by the Office of Munitions, Secretary of Defense, the following estimates of unexploded ordnance (provided in Figure 3) are based on the number and types of submunitions employed in Desert Storm and the maximum permitted lot acceptance dud rate (5%).

Air-Delivered Submunitions

	Total Expended Munitions	Calculated Number of Duds (Based on a 5% Dud Rate)
Subtotal	16,976,215	848,810

Artillery-Delivered Submunitions

	Total Expended Munitions	Calculated Number of Duds (Based on a 5% Dud Rate)
Subtotal	13,773,328	688,666
GRAND TOTAL	30,749,543	1,537,476

FIGURE 3. Estimates of unexploded ordnance (UXO) in air-delivered and artillery-delivered submunitions during the Gulf War. At an estimated 10% replacement rate per year, DoD safing, arming and fuzing requirements would represent a 3 million unit/year MEMS safing, arming and fuzing market [43].

MEMS fuze/safe-arm devices would have a number of compelling advantages. MEMS devices offer the opportunity for 5x-10x greater reliability, performance, and service life through improved safe-arming/detonating functions and inherent quality, which is currently lacking in smaller bomblet and submunition ordnance. This implies that MEMS are safer and UXO would be reduced by up to an order of magnitude. Since MEMS are smaller than conventional safing and arming devices, increased lethal volume and improved target effectiveness can be achieved in small exploding munitions. Larger caliber munitions will also benefit by incorporating multi-mode functions in one fuzing device.

Technology Adoption Issues and Hurdles: Current fuze improvement programs are geared to greater multipurpose use, or one fuze for all applications. Weapons safing, arming and fuzing is a pervasive and high-payoff MEMS insertion opportunity. Prototype devices and systems could be demonstrated in one year, with replacement of expended rounds (from training and limited future engagements) being the primary insertion route. Traditionally, fuze improvement programs have been a low priority and very expensive to implement, since safety and reliability assurance requires the testing of tens of thousands of units for each application. Early identification of systems integrators will align future safing-arming-fuzing developments to exploit the growing production of MEMS-based accelerometers and the equally stringent testing and evaluation needed for automotive safety systems. For both the competent munitions and safing, arming and fuzing applications, cost will be the primary adoption barrier. Since the combined defense market size is projected to be a fraction of the commercial market size (Figure 2), coupling of DoD inertial products to the commercial technology and manufacturing base will be critical to satisfying DoD needs.

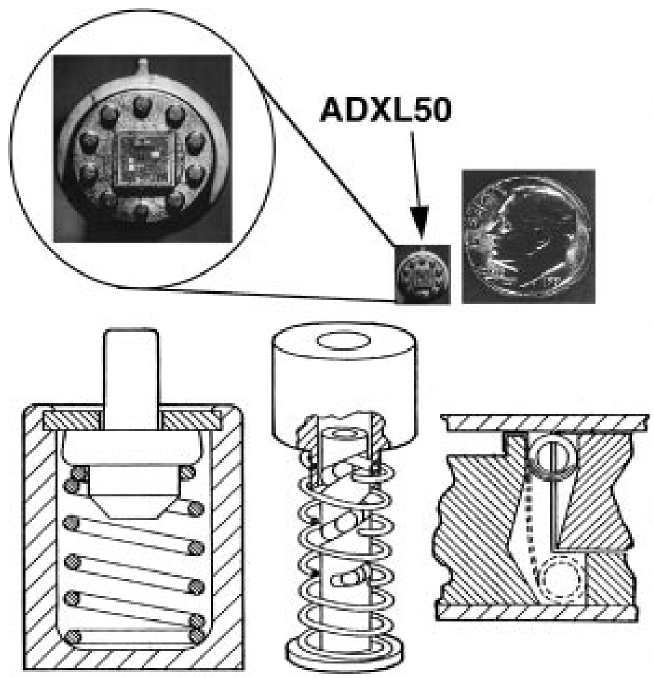


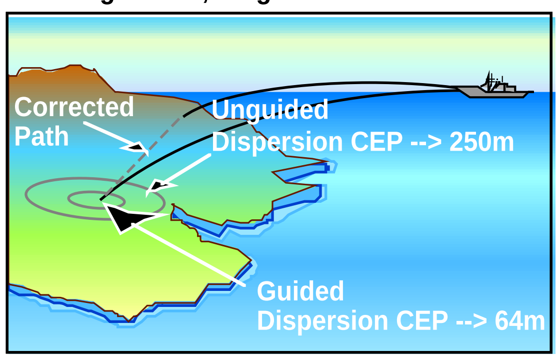
FIGURE 4. Discretely assembled acceleration sensors used in propelled munitions for conventional safing, arming and fuzing systems. Shown for comparison is the ADXL05 MEMS surface-micromachined accelerometer with similar or better performance, including self-calibration, self-testing, and self-destruction capabilities [49].

2. Competent Munitions

Integrate MEMS inertial measurement devices into conventional munitions to reduce the dispersion of projectiles on point targets.

Most U.S. weapon systems (e.g., artillery, mortars, tanks) use unguided ordnance. As a result, multiple rounds are needed to ensure that a target is destroyed. This results in high ammunition consumption rates and a significant logistical burden on supporting forces. By using MEMS inertial guidance and control in ordnance, U.S. forces would require fewer rounds to kill a target. When combined with tracking from the Global Positioning System (GPS), this technology will provide affordable precision strike without an expensive guidance seeker or nearby target designator, offering greater standoff protection for many delivery systems.

Range 30km, Target Size 20m x 30m



Number of rounds after spotting correction

Munition Type	Hit Probability	
	50%	90%
Unguided Rounds	110	364
Inertially Guided Rounds	9	30

10X REDUCTION IN REQUIRED ORDNANCE

FIGURE 5. High dynamic range accelerometer MEMS technology insertion. Inertially guided round improves accuracy and is estimated to reduce required ordnance by a factor of 10 [26].

Recent analysis has shown that a typical unguided artillery impact point dispersion of 250 meter CEP (circular error probable) requires 110 rounds to

achieve a 50 percent probability of hit on a target. Inertial guided rounds achieving a 64 meter CEP would require only nine rounds to realize the same effect. This tenfold reduction in ordnance would permit U.S. early entry forces to have significantly higher lethality with faster target engagement rates, and greater mobility and improved sustainability with less logistics burdens. Increased precision will also result in reduced collateral damage and less risk of fratricide.

Technology Adoption Issues and Hurdles: Tests have demonstrated that MEMS inertial guidance units can withstand the 30,000 g forces experienced by typical high explosive artillery rounds during launch, and up to the 100,000 g levels of advanced tank cannon-fired antiarmor munitions. This high acceleration performance, combined with low power, weight, and volume, permits the inertial guidance and control of howitzer, mortar, and rocket-fired ammunition to be implemented using a fuze-well retrofit. Much of the existing stockpile of ordnance could be quickly upgraded. Since the guidance hardware is a fuze-well retrofit for exploding ammunition, the existing munition fuze/safe-arm must also be redesigned to fit into an even smaller volume (reference application area 1). *The estimated DoD market for competent munitions is 16 million units total, with an annual peacetime requirement of 250,000-500,000 units.*

3. Platform Stabilization

Replace via retrofit or new production conventional accelerometers and gyroscopes with MEMS devices in a wide variety of DoD platforms.

In all DoD platforms, design trade-off must be made between subsystems to optimize the total system's performance. Ultimately, designers want to maximize the payload/range that a platform can provide. Any electronic/structural weight or volume that can be reduced permits designers to increase payload or range. From a tactical perspective, the increased range may now imply that commanders can use cruise missiles on a remote target, rather than risking manned aircraft. Increased payload may reduce the number of missiles that are needed to destroy a particular target, permitting more targets to be engaged.

A $30,000 missile typically contains $1,000 worth of conventional accelerometers and gyroscopes. An equivalent MEMS device, costing $20, can be directly substituted in this platform. This represents a 50x subsystem cost reduction and potentially greater reductions in space weight and power requirements. Almost any DoD system that now has a gyro or an accelerometer is a candidate for a MEMS device. This covers a broad spectrum of platforms including aircraft, missiles, tanks, and ships. MEMS gyros could be implemented in avionics, autopilots, gun mounts and stabilizers (tank turret), shipboard and radial tracking antennas, and ejection seat stabilization. *For example, each UH-60 Black Hawk helicopter contains 13 gyroscopes. All are potential MEMS insertions.*

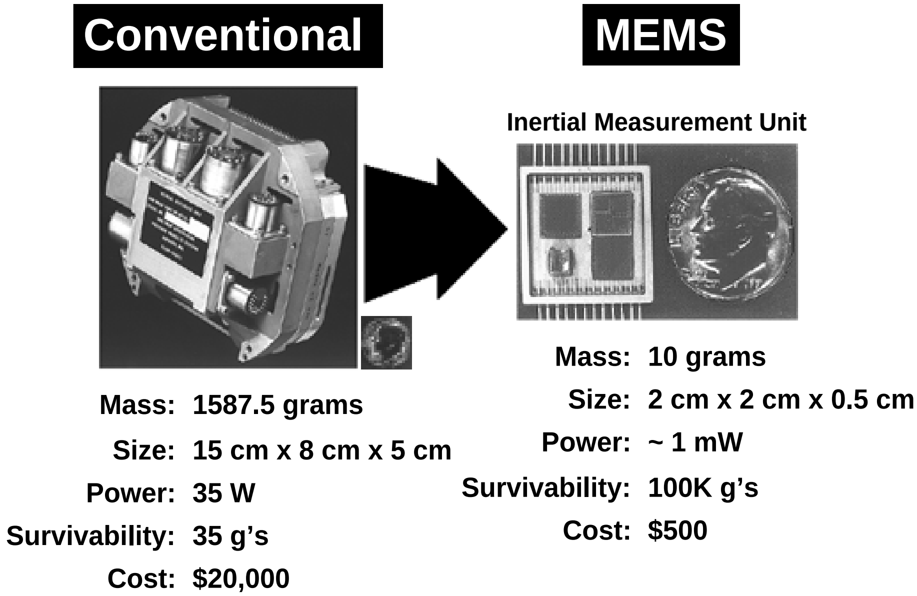


FIGURE 6. Conventional vs. MEMS inertial measurement units [19].

Technology Adoption Issues/Hurdles: To make the market financially interesting for a low cost item, one manufacturer would have to capture many different applications. Retrofit markets require many different system approvals and certifications. Early buy-in by system manufacturers is key to early DoD usage. Typical platform stabilization systems require three gyroscopes and three accelerometers. The major technical adoption issue is developing a reliable MEMS gyroscope. While MEMS accelerometers are relatively mature, current MEMS gyroscope prototypes are technically immature and unreliable.

4. Personal/Vehicle Navigation

Use MEMS gyroscopes and accelerometers integrated to form an inertial navigation unit on a chip to augment GPS in personal and vehicle navigation systems.

Accurate knowledge of position location is critical to effective joint and combined arms operations. The current proliferation of GPS receivers down to the company and even the platoon and squad level has greatly increased the ability of commanders to control the movements of large groups of soldiers and equipment. However, GPS receivers cost several hundred dollars and have battery lives measured in hours. Even if the receiver's cost and power limitations were overcome, GPS is not the panacea to solve all navigation problems in the military. GPS receivers must have direct view of 4 satellites

to achieve a 3-D position fix. Even with 4 satellites in view, location errors also occur depending on the position of the 4 satellites, making it advantageous to acquire even more than 4 satellites when determining one's location. Military forces operating in heavily wooded, urban areas, and in structures, frequently cannot get real-time position data without risking exposing themselves to enemy observation and fires.

MEMS technology can be used to develop an inexpensive, small, low power (microwatt), personal navigation device. This device would augment GPS, by updating an individual's location based on an initial GPS reference. This initial reference point may be entered periodically from the platoon or company GPS fix, depending on the gyro drift rate when performing its dead-reckoning calculations. This MEMS device would also provide continuous navigation data during periods when GPS may be jammed. MEMS personal navigations devices are currently sought by the Gen 2 Soldier Program to perform backup navigation functions. To realize this capability, new MEMS devices need to be developed.

Depending on the projected costs of the device and its display and communications functions, one device may be issued per combatant at $50 a unit. Providing a dead-reckoning feature to augment current GPS capabilities at the squad, platoon, or company level would be acceptable at a cost of $300 a unit. The size of this market is estimated at 380,000 combatants within 38,000 squads.

Technology Adoption Issues/Hurdles: MEMS gyros are currently immature and require several orders of magnitude improvement in stability over existing MEMS gyroscopes. The gyro drift rate should be low enough to make the device useful for operations of at least 2-4 hours between GPS position updates. Figure 7 presents gyroscope performance requirements and military performance requirements with those for anticipated commercial products.

There is a strong dual-use strategy that is natural to develop for the inertial measurement units identified in competent munitions, weapons safing-arming-fuzing, platform stabilization and personal/vehicle guidance. The automotive industry is a large commercial driver for the development of MEMS-based inertial measurement products. There is a large overlap between defense and commercial inertial measurement unit (IMU) performance specifications (see Figure 7). DoD investments in the design, manufacturing and evaluation tools will ensure a flexible commercial production base that can affordably be directed to procurement of defense-specific inertial measurement units. The nature of MEMS fabrication processes ensures that the relatively low-volume defense products can be obtained at the low-costs enabled by the high-volume commercial markets.

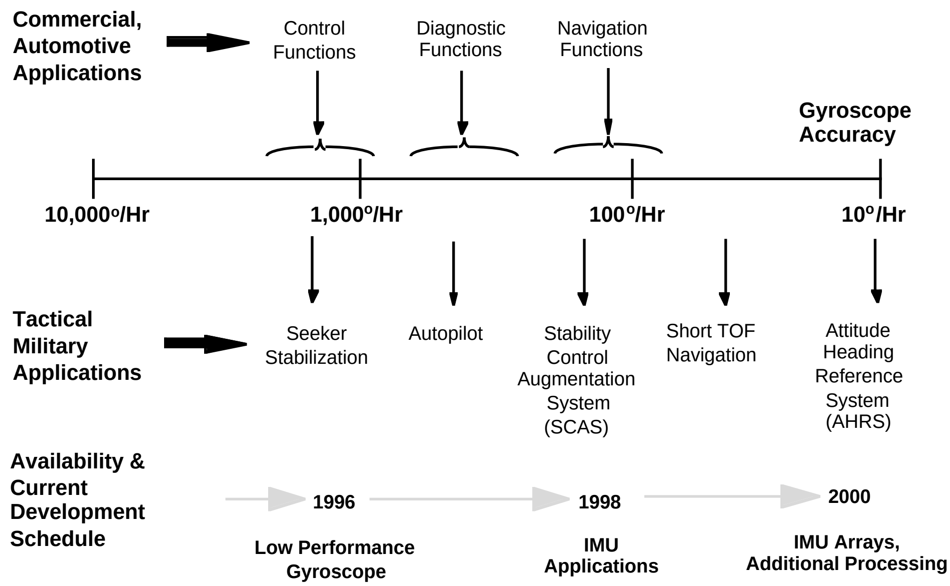


FIGURE 7. Overlap of Commercial and Defense Gyroscope Performance Specifications (adapted from data provided by Rockwell, Martin-Marietta, and Charles Stark Draper Laboratories).

B. Distributed Sensing and Control

Key applications for MEMS in distributed sensing and control include condition-based maintenance, situational awareness, miniature analytical instruments, and identify-friend-or-foe.

1. Condition-Based Maintenance

Insert MEMS devices into the components of equipment, vehicles, and aircraft to monitor and report on the status of components and materials in near-real time.

This application area would move away from performing time-based maintenance (TBM) toward condition-based maintenance (CBM). By using MEMS devices to monitor critical operational parameters including temperatures, pressures, flow rates, vibrations, surface wear rates, fluid contaminants, and accelerations, timely decisions on preventative and scheduled maintenance can be made prior to a system or component failure. MEMS-embedded weapons systems will accelerate the transition to maintenance that is dependent on the true condition of the system, and away from the present costly maintenance procedures that are based on arbitrary usage or time-elapsed measures.

Maintenance of military equipment is a time consuming task and currently costs DoD over $20 billion each year. These costs do not even reflect the salaries of military maintenance personnel. Because the physical condition of system components cannot be quickly observed or determined, much of the military's maintenance is scheduled at periodic intervals in order to prevent system failure. In helicopters, flight-critical systems need to be torn down repeatedly to physically inspect components. These maintenance actions are performed because a component failure in flight may result in loss of the aircraft and crew. While equipment is undergoing these frequent inspections, it is not available for missions.

Adopting CBM procedures enabled by embedded MEMS devices is expected to significantly reduce maintenance costs and equipment down time. Scheduled maintenance functions will be streamlined by monitoring MEMS sensors to determine precisely when maintenance is required, based on actual usage rates and measured parameters. Operators can anticipate the impending failure of components and order replacements in advance, thereby reducing equipment down time due to logistics delay. Mechanics will be able to diagnose and pinpoint failed components, facilitating troubleshooting and repair. The results of MEMS-enabled CBM procedures will be higher mission availability rates, lower maintenance costs, and improved safety records for a variety of defense weapons platforms and systems.

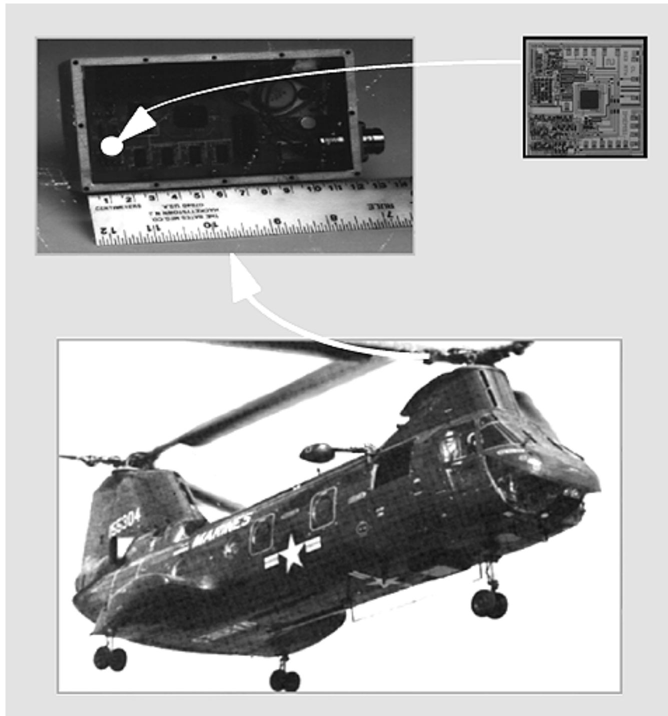


FIGURE 8. An example of MEMS condition-based maintenance on the H-46 helicopter. Accelerometers attached to each lag damper would allow immediate identification of failed operation, resulting in increased up-time and lower maintenance costs.

A focused study was performed to determine the benefit of using CBM on the maintenance-intensive H-46 helicopter used by the Navy and the Marine Corps. The study considered a number of factors such as the number of aircraft (328), annual flying hours (300 each), maintenance costs ($2400 per flight hour), and major accident rates. The study determined that the annual H-46 cost for maintenance, aircraft losses, and fatalities was $276 million. The study concluded that if an aggressive CBM program were used on this helicopter, the result would be a 50% reduction in down-time, providing improved operational availability. The H-46 would also realize $60 million savings in maintenance costs, and a 30% reduction in accidents resulting in fatalities.

Any mechanical, automotive, and aircraft system could benefit from continuous maintenance monitoring through the use of embedded MEMS devices. Systems to be monitored may include transmissions, engines, cooling systems, bearings, joints, shafts, structures, and tires. Each system and subsystem may employ from one to several MEMS devices located in different critical regions and components. Estimates of five MEMS sensors located in each of ten major system subcomponents are reasonable to monitor a diversity of maintenance parameters. This yields an estimate of approximately

50 MEMS devices per major military system, such as trucks, tanks, personnel carriers, helicopters, major weapons systems, and aircraft, of which there are at least 100,000 in service. Although the actual number of MEMS devices per system will vary depending on system complexity, MEMS requirements could total approximately 50,000,000 devices considering all applications. The average cost of MEMS accelerometers is currently less than ten dollars per device. Further price reductions will enable widespread proliferation in the maintenance community.

One specific example of condition-based maintenance is **tire temperature and pressure sensing**. In this application, MEMS pressure and temperature sensors will be embedded into the sidewalls of tires. These sensors will transmit temperature, pressure, and number-of-rotations information to a hand-held receiver used by the maintenance and service personnel. This application is a subset of condition-based maintenance identified previously, but is discussed in detail because it is relatively mature and will be available in the near term. This application offers vehicle operation and maintenance savings, achieved through reduced labor, fuel loss, tread wear, tire disposal, vehicle down time, and dependence on foreign oil. One case study shows an average savings of $19 per tire, on an average tire price of $200 for large vehicles, or approximately 10% of the tire cost.

Technology Adoption Issues/Hurdles: MEMS will have to be extensively tested and evaluated under all circumstances in order to provide highly reliable information on a particular system and component. Operators and mechanics will have to develop confidence in the information being provided by the MEMS sensor without directly observing the component in question. Physical packaging issues of MEMS sensors will need to address power and communications issues. In some cases, stand alone, self powered devices using a wireless interface will need to be developed.

2. Situational Awareness

Develop MEMS devices that can be used in a variety of distributed military applications, including perimeter security, shipboard automation, monitoring tides and climate, and area surveillance.

The need for unattended sensors has arisen from many generic and specific applications since the Vietnam War. Typically, systems have been used to monitor high interest but non-permissive areas, such as to detect enemy logistics traffic on suspected supply routes. However, current devices are typically large, expensive, and limited in sensitivity and discrimination of targets.

Small, low cost (disposable) sensors are needed to perform a broad spectrum of missions. Tactical forces require these sensors, embedded at a set perimeter range, to detect sound and motion. These sensors could have a 200-400m RF link to alert friendly forces about nearby enemy activity.

Prior to entry into nonpermissive areas, sensors could be emplaced by reconnaissance teams to monitor and record soil conditions, tides, temperatures, precipitation, local environmental activity (e.g., sand storms), and other important data. This information is needed to help determine the time and place of attack, vehicle trafficability, and special equipment requirements. Networks of ground sensors could also be distributed in the deep battle area to cover gaps in radar coverage or monitor areas of interest. These deep networks could be delivered by artillery, aircraft, or reconnaissance forces and possibly use an RF or satcom link. Distributed sensors could automate many functions performed in the military. For example, shipboard automation can help detect fires and actuate fire control equipment.

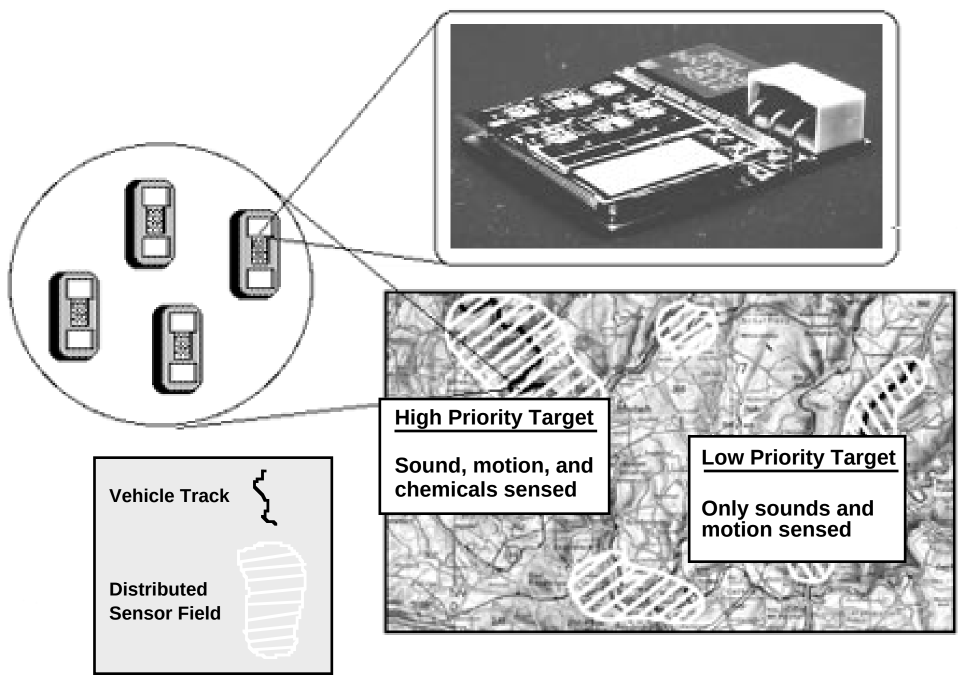


FIGURE 9. Unattended ground sensors in a ground surveillance scenario, serving as a means for intelligence collection. These low-power sensors would use MEMS sensor clusters and wide-area wireless power and communication techniques [19].

MEMS offers the opportunity to improve current unattended sensors. Current sensor packaging is power and volume limited, and reliability can be degraded during air deployment. MEMS permits incorporation of multimode sensing at greatly reduced space, weight, power, and cost. MEMS devices are inherently more rugged so that they can be deployed by a variety of delivery systems. The small size, weight, power requirements, and cost of

MEMS can enable the development of disposable sensors for tactical perimeter security or for monitoring local climate conditions (Figure 9).

For all of the conceivable applications, from the tactical to the theater-army level, the market can be reasonably estimated at several million sensor units costing in the $1 to $10 range. Tactical perimeter receivers would not be considered disposable devices and several could be issued down to the platoon level, of which there are approximately 10,000. This application could be developed in the relatively near-term.

Technology Adoption Issues/Hurdles: With appropriate investment, tactical perimeter sensors are on the near horizon. Less than a dozen sensors could be required to provide improved perimeter security for individual tactical units. These small networks could be easily managed using conventional multiplexing techniques. The most technically challenging application is a large-scale distributed unattended ground sensor network. As sensor functions and networking activities become more complicated, the requirements for pre-processing data is essential to avoid over-loading decision makers. Advances will be tightly coupled to advances in low-power electronics and wireless technologies, and will need investment in systems design and development.

3. Miniature Analytical Instruments

Develop small, low cost, highly portable MEMS analytical instruments with equivalent or greater performance than large laboratory spectrometers and other conventional chemical identification devices.

The quick detection and identification of substances such as volatile fluids (fuels), explosives, and drugs are of strong military interest. Chemical and biological agents are a continuing and pervasive threat. Recent chemical agent attacks on the Tokyo Subway System highlight the ease and lethality with which these attacks can occur.

DoD needs user-friendly, miniature devices that can be used to perform key missions, such as nuclear, biological and chemical (NBC) operations, treaty verification, cargo inspections, and detecting/identifying fuels, explosives and illegal drugs. For example, current US chemical agent alarms (M8A1) are too bulky and heavy for individual use. Training US forces on detection (M256 Kit), identification, and response/decontamination procedures, to maintain minimal proficiency, is a constant challenge. At the outset of Desert Storm, there were no mechanisms to detect biological agents until after medical symptoms occurred. Later, a limited number of NBC recon systems were deployed and reportedly worked well, but the equipment had to be maintained by contractor personnel. High temperatures also shortened the battery life of current NBC detectors.

MEMS research and development progress in the next five years can result in a variety of small, low-cost, low-power portable analytical instruments with compact versatility and a built-in self-test/calibration feature. For

example, an ideal MEMS NBC detector would be provided integral to each gas mask, with a small display. Such detectors could also be mounted on other items of military equipment. MEMS devices would enable the quick detection, alarm, and identification of threat agents. These devices could also verify that decontamination efforts were effective. This capability would eliminate the requirement for many specialized teams that must currently be dispatched to a reported contamination site.

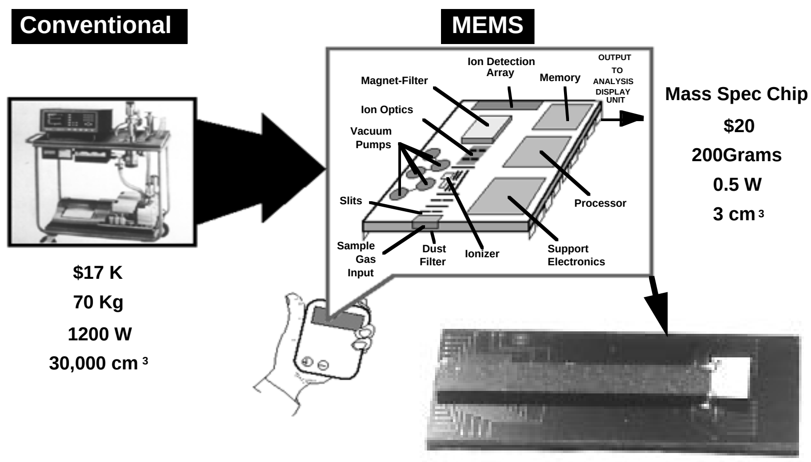


FIGURE 10. Mass spectrograph on a chip, which integrates vacuum pumps, ionizer, an ion detector array, and control electronics onto a monolithic chip architecture [19].

The market for individual NBC detectors (possibly implemented in gas masks) is estimated at 2,000,000 units with a MEMS cost of $25 per unit. Applying several of these detectors to the outside and inside of all military vehicles and major weapons systems could add an additional 500,000 unit market depending on the number affixed to each item of equipment. A handheld detection device at $100 each is estimated to command at least a 100,000 unit market in various chemical, drug, and explosive detection fields.

Technology Adoption Issues/Hurdles: The need to develop better and more portable chemical detecting devices is not a new requirement in government and industry. Both are poised to make large scale use if suitable detectors are realized. The significant challenge is developing the extensive spectrum database of all the chemicals of interest in various industrial and government applications. With literally thousands of chemicals of interest, the investment in developing the database applicable to the detection methodology is significant. Additionally, the handheld MEMS devices are targeted to be three orders of magnitude cheaper than conventional systems, with a 350x reduction in weight and a five order of magnitude reduction in power

consumption. Another major technical hurdle involves demonstrating the long-term stability of MEMS analytical instruments.

4. Identify-Friend-or-Foe (IFF)

MEMS modulation of deformable and active surfaces, together with optics, may make a viable identify-friend-or-foe systems with built-in self-test, secure communications, or a smart reflector.

Modern combat is characterized by rapid, violent, and continuous operations (day and night), in all weather, and on nonlinear battlefields. US equipment can detect and destroy a target at longer engagement ranges--well before it can identify it. A well-trained tank crew can detect and engage a target in less than six seconds. The combination of fatigue, smoke, dust, haze, rain, darkness, and poor communications can add to the confusion. Ground target ID is a serious problem. Combined forces often use the same equipment as the enemy, further complicating identification.

There were 28 fratricide incidents involving US forces in Desert Storm, mainly involving ground vehicles. These incidents resulted in 35 of 146 deaths, and 72 of 467 wounded in combat operations. In comparison, of the 38 fixed wing aircraft lost in the war, none were lost to friendly fire. This is largely attributed to the fact that aircraft have traditionally employed sophisticated IFF technology, and the establishment of coalition air supremacy.

The greatest advantage of MEMS technology is that sophisticated mechanical devices and their associated electronic control can be made small, low power, and inexpensive, permitting the device to be proliferated over the surface of a vehicle, individual, or item of equipment. A passive, reflecting MEMS IFF device may also have inherent security in that the IFF logic is effectively invisible. The interrogation signal may also be coded to provide the IFF confirmation instructions so that obtaining the MEMS device does not compromise security. The MEMS IFF device could be designed to “self-destruct” if removed from its mounting location in a one-time-mount concept.

DoD Market:If IFF devices were only used on ground combat vehicles, the military requirement would be about 15,000 systems (each system may have up to 10 MEMS devices). If IFF were more broadly applied, there are an estimated 100,000 items of military equipment which would benefit from a MEMS system. Personal IFF could also account for an additional 380,000 systems for combatants.

Technology Adoption Issues/Hurdles: While MEMS IFF devices are envisioned, no investments or prototyping attempts have been made. Reliability of MEMS IFF devices will be a key issue. Because these devices will be operational at night and subjected to extreme environmental and physical abuse, operation in the infrared and rugged physical packaging are issues that will need to be investigated and addressed.

5. Biomedical Devices

Use MEMS devices for monitoring vital signs of combatants and in delivering trauma care.

Medical devices are currently one of the most mature MEMS markets, with sales of disposable pressure sensors for various applications approaching 19 million units per year. The MEMS medical market is still growing as technical advances and new applications arise. A significant DoD effort in this area is the Personal Status Monitor (PSM). PSM is designed to monitor individual bodily functions including heart rate, blood pressure, blood oxygen, core body temperature, respiration rate, and hydration.

Most combatants killed in action die during the first hour after injury. In many cases, early medical treatment may prevent wounds from being fatal and increase the survival rate of combatants. To enable earlier lifesaving intervention, casualties must be located more quickly and their medical condition diagnosed and treated faster. Continuous and automatic monitoring of vital signs permits one medic to provide more efficient treatment to multiple casualties, and helps the establishment of telemedicine.

MEMS sensors, integrated in a device like the PSM, can help determine the medical status of individual combatants, expedite diagnosis and treatment during the golden hour, and help medical personnel prioritize care (triage). These sensors will provide important information, such as blood pressure, temperature, oxygenation, and respiration.

Technology Adoption Issues/Hurdles: Manufacturer liability is a significant technology adoption issue for MEMS biomedical devices which are designed to be embedded within the human body. Such devices require extensive testing and evaluation in order to be granted regulatory approval.

6. Active Structures

Embed or apply MEMS devices to materials and structures to enable on-demand and programmable surface and material properties.

Aircraft development requires continued efforts to squeeze every ounce of performance into a design so that aircraft can travel faster, farther, with greater payload and maneuverability, and higher efficiency. MEMS will permit development of more maneuverable, more efficient high performance aircraft. An example of an active, deformable MEMS array used for aerodynamic control is presented in Figure 11.

Active deformable surfaces could also be applied to rotor blades on helicopters to achieve greater lifting efficiency, on submarine surfaces to reduce noise, and as advanced sonar with multiple arrays. MEMS devices can be surface mounted or embedded into advanced and conventional structural members to monitor static and dynamic loading conditions and then react to provide localized strengthening as required. In weight-critical applications,

increasing the strength to weight ratio of structural components offers improvements in performance.

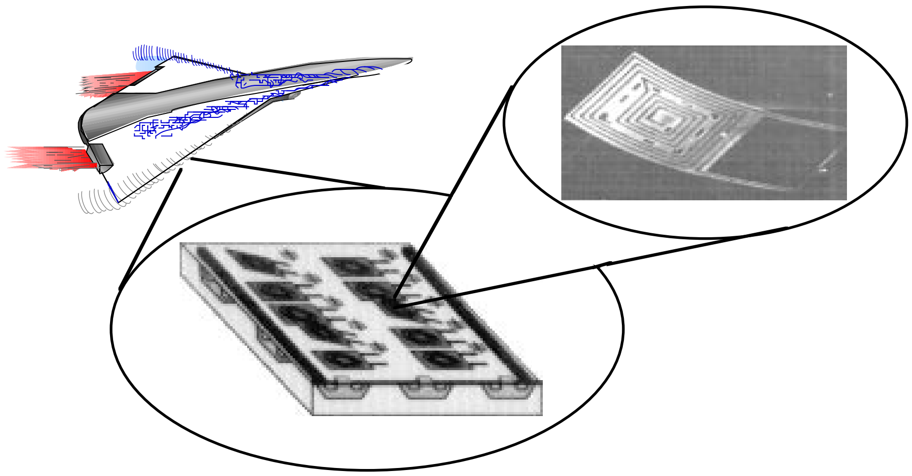


FIGURE 11. Conformable microactuator flaps for aerodynamic control. By disturbing the vortices at the separation layer of the wing, these microactuator arrays will result in reduced drag and higher maneuverability of the aircraft [19].

For space applications, reducing structural weight and volume, while retaining system performance, can result in greatly reduced deployment costs. Weight critical systems, such as spacecraft and aircraft and their payloads may realize greater weight efficiency and, hence, reduced operating and lifting costs.

Technology Adoption Issues/Hurdles: An adequate cost/benefit analysis as compared with other emerging technologies is required. Active deformable surface concept demonstrations for turbulence control have not yet been conducted.

C. Information Technology

As a response to the information-driven battlefield, DoD applications requiring rapid transfer, retrieval, and display of enormous amounts of data have been identified in MEMS, particularly in mass data storage and displays.

1. Mass Data Storage

Provide MEMS-based and MEMS-enhanced data storage devices to enhance current memory drives with a capability that would offer more than 100 times increase in data storage capacity.

Mass data storage requirements continue to increase as the military moves toward increased digitization. Tactical computing systems must be small, light, and often low power to be useful to highly mobile forces. For example, a dismounted reconnaissance team would need a system that could hold several digital maps, photographs, field manuals, and databases - potentially requiring 10 GB or more of storage. No portable, battery-powered data storage system exists that can support this need.

Both MEMS-enhanced conventional magnetic disk drives and future atomic-resolution data storage systems fabricated on silicon substrates and integrated with signal processing electronics will substantially decrease the size, weight, power requirements, latency of access, failure rate, and cost of data storage. Advanced tunneling-based write-once, read-many-times (WORM) devices offer as much as 100,000 times the storage density of a current CD-ROM. Micro disks, when coupled with advances in low-power computing and displays, would enable major advances in portable electronic devices.

The digitized battlefield will need to be supported by major advances in data storage capability. Much of DoD's portable and mobile information storage requirement can be satisfied by MEMS technology. Lower cost memory in smaller volume is ideal for 3-D mission planners, map storage, mission plans, technical manuals, training schedules, and real-time intelligence analysis. If this technology were only applied to portable devices, it is easy to envision one digital assistant (with an embedded MEMS disk drive) being issued to each service member. This would result in a minimum DoD market of 1.5 million units.

Technology Adoption Issues/Hurdles: There is a high cost associated with converting, updating, and distributing tech manuals and other DoD information in digital form. However, there currently is an ongoing effort to put many of these manuals in electronic format. In the long run, the requirement for hard copy manuals would be drastically reduced. The mass data storage market is dominated by commercial users. MEMS-based data storage systems will need to compete on a cost and performance basis with other data storage devices, such as high-density solid state and optical drives.

2. Displays

MEMS devices for small-area, low-power and high resolution display applications. Reflective micromirror devices (e.g. the digital micromirror display) also offers the potential for a large projection screen for command and control applications.

The digitized battlefield demands large quantities of information at every level, from commander to individual combatants. Command posts and operations centers are normally shipboard, or ground based in a building or tent. These cells perform command, control, planning, and logistics functions over a large area of responsibility. In these environments, large displays are needed to depict maps, operational graphics and text data.

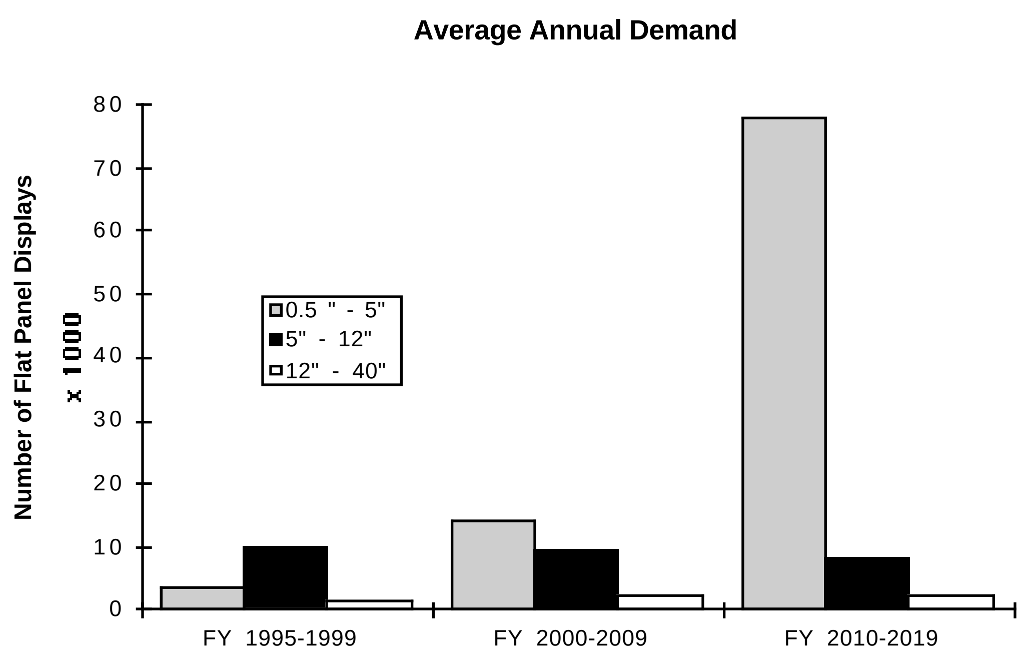
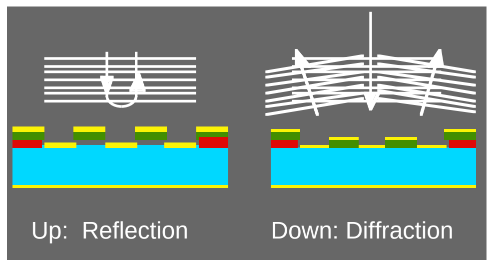


FIGURE 12. Defense flat panel display (FPD) demand projection, showing the average annual demand for FPDs. The primary driver is the 0.5”-1.0” FPD for micro-displays. Source: Building US Capabilities in Flat Panel Displays, Department of Defense, October 1994.

At the other end of the spectrum is the individual warrior. This person has a requirement to perform similar functions but on a smaller scale. A low power, personal display is needed to provide the individual warrior with all the necessary information (e.g., maps, technical manuals, photographs, mission plans). Figure 12 plots the DoD display requirements cited in the 1994 document “Building US Capabilities in Flat Panel Displays,” Department of Defense. In this projection, DoD display requirements are dominated by

0.5”-1.0” microdisplays, the size and form factors that are best addressed by silicon-based, micromachined devices.

A small-area, low-power, high-resolution MEMS display recently demonstrated is the Deformable Grating Light Valve. Figure 13 shows the principle of operation along with a map image with the high resolution possible using the DGLV. Micromachined beams can be electrostatically deflected up or down to create reflective and defractive pixels respectively. Depending on the width and spacing of the beams, different full-color video displays are possible.



a)

b)

FIGURE 13. a) Deformable grating light valve (DGLV) operational principle, and b) image created with DGLV [19].

Technology Adoption Issues/Hurdles: MEMS-based displays must compete with other display technologies in terms of cost, performance and reliability. Display applications expected to best exploit the form-factor, performance, and cost of MEMS-based devices are mobile, personal displays in the 0.5”-5.0” size range.

MEMS Market and Industry Structure

MEMS Market

Forecasts for MEMS products throughout the world show rapid growth for the foreseeable future. Early market studies projected an eight-fold growth in the nearly $1 billion 1994 MEMS market by the turn of the century. More recent estimates are forecasting growth of nearly twelve to fourteen times today's market, reaching $12-14 billion by the year 2000 (Figure 14). While sensors (primarily pressure and acceleration) are the principal MEMS products today, no one product or application area is set to dominate the MEMS industry for the foreseeable future, with the MEMS market growing both in the currently dominant sensor sector and in the actuator-enabled sectors. Furthermore, because MEMS products will be embedded in larger, non-MEMS systems (e.g., automobiles, printers, displays, instruments, and controllers), they will enable new and improved systems with a projected market worth approaching $100 billion in the year 2000.

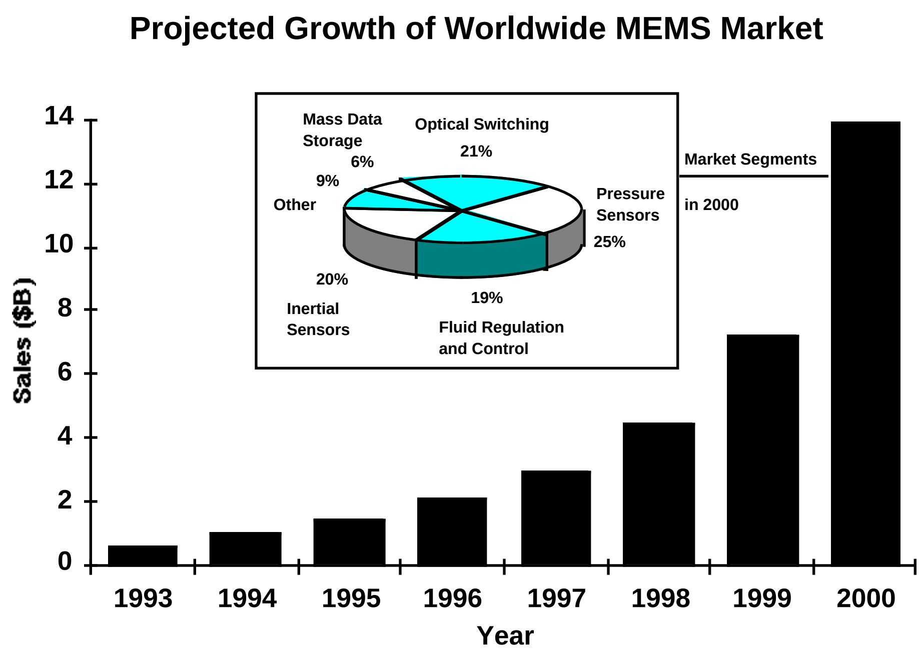


FIGURE 14. Projected worldwide MEMS market. Note inset pie chart that shows the non-sensor market segments in fluid regulation and control, optical systems and mass data storage are projected to be about half of the total market by the year 2000 [25,18].

Present MEMS markets and demand are overwhelmingly in the commercial sector, with the automobile industry being the major driver for most micromachined sensors (pressure, acceleration and oxygen). In 1994 model year

cars that were manufactured in the US, there are an average of 14 sensors, approximately one-fourth of which are MEMS-based sensors, increasing in number at a rate of 20% per year [21,41,45]. As one example, a manifold pressure sensor is currently installed in vehicles by all three major US automakers. This amounts to more than 20 million micromachined manifold pressure sensors being manufactured per year.

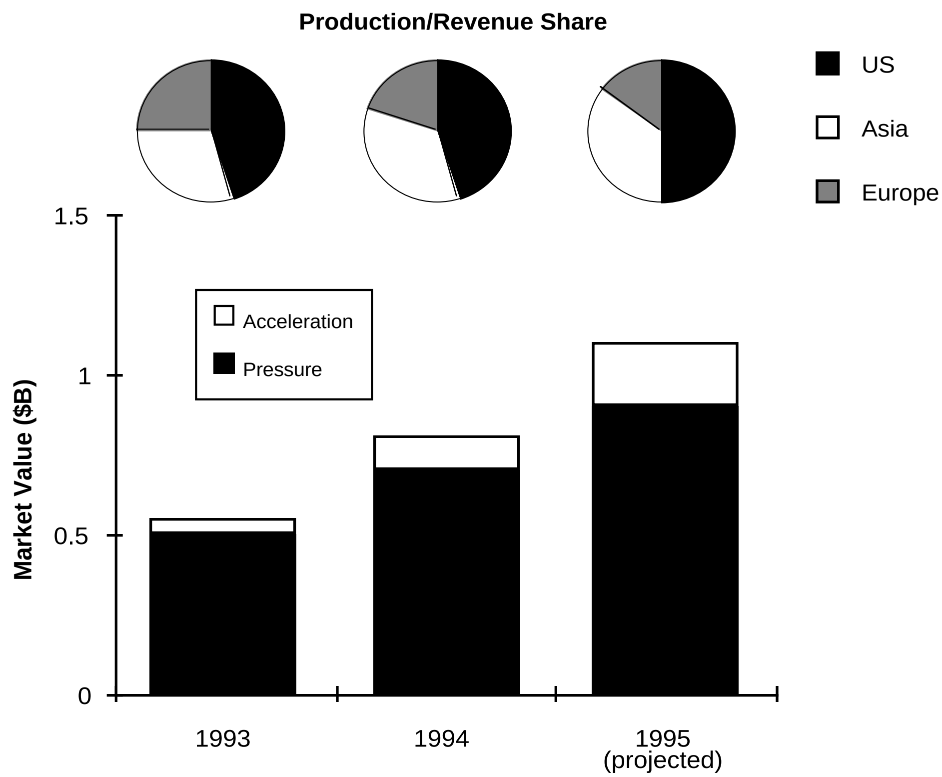


FIGURE 15. Worldwide annual pressure and acceleration sensor markets with associated (on top) regional production and revenue percentages for the combined sensor markets [25].

More recently, the market for accelerometers used in airbag deployment systems has also grown. Nearly 5 million micromachined accelerometers for airbag systems were manufactured and installed in 1994 vehicles. Biomedical sensors, particularly disposable blood pressure and blood chemistry sensors, are fast approaching the automobile industry in both sensor unit numbers and market size. Over 17 million micromachined pressure sensors, with a market value of nearly $200 million, were manufactured, used and disposed of in 1994.

While the MEMS sensors market will continue to grow, particularly sensors with integrated signal processing, self-calibration and self-test (pressure sensors, accelerometers, gyroscopes, and chemical sensors), a substantial

portion of the growth in the next few years (and of the MEMS market by the year 2000) will be in non-sensing, actuator-enabled applications. These applications include microoptomechanical systems, principally in displays, scanners and fiber-optic switches; integrated fluidic systems, primarily in fuel-injections systems, ink-jet printheads, and flow regulators; and mass data storage devices for both magnetic and non-magnetic recording techniques. Two non-sensor markets alone, printing and telecommunications, are projected to match the present sensor market size by the year 2000 [25,40,41].

MEMS Industry Structure

Those companies which have so far been directly involved in producing MEMS devices and systems are manufacturers of sensors, industrial and residential control systems, electronic components, computer peripherals, automotive and aerospace electronics, analytical instruments, biomedical products, and office equipment. Examples of companies manufacturing MEMS products worldwide include Honeywell, Motorola, Hewlett-Packard, Analog Devices, Siemens, Hitachi, Vaisala, Texas Instruments, Lucas NovaSensor, EG&G-IC Sensors, Nippon Denso, Xerox, Delco, and Rockwell. Of the roughly 80 US firms currently identified as being involved in MEMS (Figure 16), more than 60 are small businesses with less than ten million dollars in annual sales [18,25]. The remaining 20 firms are large corporations distributed across different industry sectors with varying degrees of research activities and products in MEMS (the front cover of the 1993 annual shareholders' report for Hewlett-Packard featured a MEMS flow-valve developed for use in their analytical instruments division).

Of the more than 200 firms currently identified as having activity in MEMS, more than 80 are in the US, about 75 are in Japan, about 35 are in Germany, and the remainder are distributed among the other major European countries (Battelle Institute Study, 1992).

Of the nearly $300 million worldwide market in pressure sensors, US manufacturers account for nearly 45% of production and revenue. In the growing accelerometer market, the US position is very similar. Of the nearly 5 million accelerometers made in 1994, US manufacturers accounted for nearly 50% of the market. Because of the combination of an advanced technology base and a strong manufacturing capability in these two key sensor areas, US manufacturers are poised to expand their MEMS market share and are already beginning to penetrate both the European and Japanese automotive sensors market. Accounting for slightly more than half of the worldwide MEMS manufactured products and revenue, the US MEMS industry is a major player in all key segments of the world MEMS market.

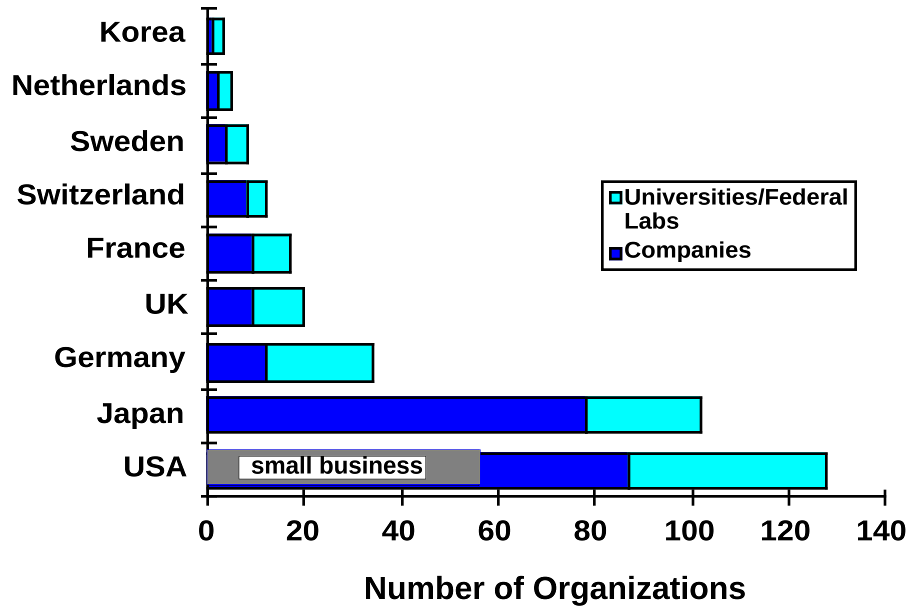


FIGURE 16. Distribution of organizations worldwide with activities in MEMS. Note the large number of US small businesses active in MEMS [18, 25, 42].

Europe leads the US and Japan in the research, development and manufacturing of micromachined biomedical sensors and instruments, particularly blood chemistry sensors and drug-delivery systems. In process development, Germany was the first to develop (and begin commercializing) a high-aspect ratio fabrication process based on X-ray exposures (see Appendix: MEMS Technology). In Japan, few MEMS products aside from sensors are being manufactured. However, intense and extensive MEMS R&D programs are being pursued in the central research laboratories of all of the major Japanese electronics corporations. In addition to the traditional Japanese components and consumer electronics manufacturers, heavy industry firms including steel and chemical concerns (e.g., NKK, Kirin, Mitsubishi) are also making investments in MEMS as they diversify to high technology products. For these heavy industry firms, MEMS represents an opportunity to establish a presence in a high-technology, semiconductor-like industry where, unlike microelectronics, no dominant products or manufacturers exist.

European semiconductor equipment manufacturers are taking the lead in developing fabrication equipment targeted and optimized for MEMS manufacturing requirements. Advanced etching (France, UK) and bonding (Germany) equipment are increasingly being purchased by US MEMS manufacturers to meet production needs. Not surprisingly, since MEMS photolithographic needs are similar to those of microelectronics, Japanese photolithography equipment manufacturers will also supply MEMS manu-

facturing photolithography needs. Given the close ties between MEMS manufacturing and microelectronics manufacturing, there is currently no MEMS equipment and materials suppliers' infrastructure separate from the microelectronics fabrication infrastructure. With MEMS markets and production requirements projected to be a fraction of those for the microelectronics industry, this is not likely to change for the foreseeable future. The US maintains a global position in most classes of semiconductor manufacturing equipment which will form the basis of the MEMS fabrication infrastructure. The semiconductor manufacturing equipment infrastructure is the subject of a separate assessment that will be completed in the near future. Any shortfalls in the infrastructure will be identified and addressed through the semiconductor manufacturing equipment assessment.

With one notable distinction, the MEMS industry structures in the US, Europe and Japan are very similar. Those companies which have so far been directly involved in producing and using MEMS are a broad mix of manufacturers of sensors, industrial and residential control systems, electronic components, computer peripherals, automotive and aerospace electronics, analytical instruments, biomedical products, and office equipment.

The notable distinction in industry structure is that few small businesses in Europe or Japan are involved in MEMS. In the US, nearly 60 of the 80 identified firms with MEMS activities are small businesses, each typically generating on average less than five million dollars in annual revenues. Most of these businesses do not have or need their own dedicated fabrication resources. New approaches to the development of manufacturing resources can both exploit this distinctive structure for DoD-specific needs and accelerate the innovation and commercialization of MEMS products. Given the varied applications of MEMS devices and the most likely evolution of their associated fabrication processes, the development of support and access technologies will be even more important and challenging in MEMS manufacturing than in microelectronics manufacturing.

Unlike microelectronics, where a few types of fabrication processes satisfy most microelectronics manufacturing requirements, MEMS, given their intimate and varied interaction with the physical world, will have a greater variety of device designs and a greater variety of associated manufacturing resources. For example, the thin-film structures created using surface micromachining techniques, while well-suited for the relatively small forces encountered in inertial measurement devices, are not adequate for MEMS fluid valves and regulators. Similarly, the thicker structures created using a combination of wafer etching and bonding while well-suited to the higher forces and motions in fluid valves and regulators consume too much power to be used for the fabrication of microoptomechanical aligners and displays. There is not likely to be a MEMS equivalent of a CMOS (complementary metal oxide semiconductor) process like that in microelectronics that will satisfy the majority of MEMS device fabrication needs.

These different MEMS fabrication processes will often be developed by larger firms with a particular and large commercial market as the target.

Typically the firm developing the manufacturing resources needs to be focused on the production of products for those one or two driving applications. But, in most cases, once the manufacturing resource is developed, numerous (hundreds) of products for smaller (<$10 million per year) markets could be addressed with the same manufacturing resources. No single one of these smaller markets would have justified the development of the fabrication process. For the firms that have developed the manufacturing resource, addressing small and fragmented markets is not presently economically justifiable given the market diversity and the current state of electronic design aids. Most of these specialized markets will only be attractive and economically justifiable to smaller businesses who, however, do not have (nor would they want to duplicate) the manufacturing resources.

By gaining access to manufacturing resources through a domestic MEMS infrastructure, businesses would be in a better position to field competitive MEMS products and also be able to use existing resources at higher capacities, speeding return on investments for those companies with the resources. Furthermore, since most MEMS defense applications and products are some of these smaller and fragmented markets, access to MEMS manufacturing resources would also support rapid and affordable fielding of MEMS defense products.

One step towards acquiring a national MEMS manufacturing infrastructure is to make product-neutral investments in the development of support and access technologies that include;

- *electronic design aids for the free-form MEMS device designs and coupling of simulation tools for the variety of physical effects and properties encountered in MEMS applications,*
- *better understanding and control of processes to assure repeatable and predictable mechanical and other non-electrical properties of materials,*
- *manufacturing equipment optimized for MEMS requirements (thicker film deposition, deeper etching, handling and packaging techniques which selectively contact and seal portions of the MEMS device), and*
- *measurement tools and techniques that characterize electrical and other performance parameters (e.g., motion, fluid flow) for operational testing and device qualification.*

Since most DoD applications will be early drivers of advanced MEMS devices or require the adaptation and qualification of commercial devices, DoD investments in the manufacturing resources serves not only its own needs for rapid, flexible and affordable access to MEMS technology but does so in a way that complements and enhances the US industrial capability in MEMS.

US Position and Growth in the Global MEMS Market

For the existing MEMS markets and products in pressure sensors and accelerometers, US manufacturers are still internationally competitive. As

MEMS products address the larger class of actuator-enabled applications and evolve to higher levels of functional capability, higher levels of integrated electronics, and greater numbers of mechanical components, future competitiveness will be paced by the ability of manufacturers to shift from discrete MEMS component manufacturing to the manufacturing of integrated MEMS devices. The MEMS products of the future will not only be a mix of actuator-enabled products and sensors, but devices with more highly integrated and larger numbers of mechanical and electrical components.

In MEMS pressure sensors and accelerometers the US has a strong market position and, in accelerometers, one that is growing. Of the $400 million worldwide market in pressure sensors, US manufacturers account for about 55% of the manufactured sensors and revenue, with most being produced at a handful of major manufacturers. Looking at the inertial sensor market and one automotive sensor in particular--the accelerometer that deploys the airbag in an accident--we see a representative MEMS product and market projection. Although the number of cars that will be manufactured worldwide is projected to remain at a flat 45-50 million units per year until the end of the century, the number of accelerometers embedded in those automobiles is projected to grow by 15-20% per year. At present about 25% of manufactured cars have airbags; this figure is expected to reach nearly 70% of manufactured cars by the year 2000. During the same period that more airbag safety systems will be manufactured and installed, the technology for the accelerometer is also shifting from the present discrete component systems to single-chip, monolithic micromachined accelerometers with integrated electronics. In this one MEMS application alone, US technology is well in front, with US manufacturers positioned to have nearly 60% of the projected $300 million air-bag sensor market in the year 2000 [25,40 45].

Future MEMS products will demand yet higher levels of mechanical/electrical integration and more intimate interaction with the physical world. As one example, the ink-jet printer printhead (an example of a MEMS fluid regulation and control device) is a key MEMS component for the major computer peripherals and instruments manufacturers. As part of printers and to a lesser extent, analytical instrument, MEMS printheads and disposable ink-jet packs are manufactured (presently primarily overseas by, among others, Canon and Hewlett-Packard) and assembled as part of larger, more complex products. Printer sales worldwide are growing by 20-25% per year, with 1994 sales at nearly $12 billion dollars [25,40,42]. Of that market, ink-jet/MEMS-based printers represent about 25% of the market and the fastest growing segment of the market. Today, Japanese companies have the lead ink-jet printing technology (a thin-film, edge-ejecting printhead) and are component suppliers to the major US manufacturers of computer peripherals. As the mass-market printer products (personal laser-quality printers selling for retail prices of $1000-1500) transition from predominately black and white to color over the next 2-5 years, the industry is poised for a technology revolution in the design and manufacture of print engines. MEMS-based ink-jet printing technology offers the required resolution and speed at a cost that is unmatched by other technologies (laser xerography, thermal transfer, or sublimation). Printers represent a good example of the way in

which embedded MEMS components will enable improved or new larger systems and markets. While a MEMS ink-jet printhead may only be a $100 component and a $1 billion MEMS component market, the MEMS printhead will be the key element in making it possible to field a $1000 color printer and capture a much larger $10 billion systems market.

Just as individual transistor circuits with discrete components gave way to integrated circuits, the individual MEMS devices of today will give way to integrated MEMS with larger numbers of mechanical components and higher levels of integrated electronics. The US is poised to exploit a strong MEMS science and technology base and an early lead in the fabrication of integrated MEMS devices. By making investments that will accelerate the transition to integrated MEMS technology, the US can develop and provide early access to superior MEMS technology for DoD needs and complement industry investments that are being made to maintain a robust domestic MEMS manufacturing base.

Global Investments in MEMS

Combined US federal funding of MEMS R&D will reach approximately $35 million per year in fiscal year 1995. Starting in 1988, the National Science Foundation has been funding basic MEMS research at roughly $2-3 million per year. DoD funding (primarily at ARPA and beginning at about $5 million in 1992) in 1995 represents nearly $30 million of the annual amount, NSF roughly $3 million, and the remainder is distributed among other agencies and the national laboratories. To date, federal dollars have primarily been directed at basic science and advanced device and process technologies. About ten percent of funds have focused on systems design and development and less than ten percent of funds have been directed towards support and access technologies (electronic design aids, shared fabrication services, manufacturing equipment, packaging/interface techniques, and test/evaluation tools).

In 1995, the size of government-funded MEMS R&D programs in Japan is approximately $30 million and in Europe about $40 million. The bulk of Japan's investments are from a Ministry of International Trade and Industry (MITI) Micromachines Project started in early 1991. The ten-year Micromachines Project is being funded at $25 million per year and is, unlike the US and European programs, currently focused more on extending conventional machining and assembly techniques rather than on the semiconductor-based fabrication technologies. The MITI Micromachines program is aligned along focus areas of materials, actuation technologies, micromanipulation and assembly techniques, and energy sources. These focus areas are structured around a central, integrating theme of realizing an autonomous vessel capable of traveling along pipelines in a nuclear reactor or for biomedical applications. Member organizations include nearly forty Japanese firms from diverse industry sectors (e.g. Olympus, Matsushita, Sumitomo, the National universities) and, as part of the recent international element in this and other MITI projects, an Australian university and a US research firm. Industry participants are expected to match MITI funds and many firms typically put in more so that total funds expended on the Micromachines Project are estimated to be above $50 million per year [21]. The MITI Micromachines Project is approaching its mid-term evaluation point (set for the spring of 1996) and early indications are that, despite reductions in the overall program to approximately $20 million per year, microelectronics-based MEMS will become a larger part of the Project's focus and will receive a greater share of project resources [21, 40, 42].

European programs, mainly in Germany and Switzerland, started in 1990 and 1992 respectively and are, like US programs, focused on microelectronics-based fabrication techniques. Starting in 1995, France will coordinate and consolidate its microelectronics-based microsystems research activities across the various government departments supporting science and technology. Total French government funds for MEMS research and development are expected to reach nearly $10 million per year by 1996. Since 1993 and under the auspices of the European Community, the different MEMS pro-

grams have formed a coordinating body that meets regularly with representation from the major national programs (Germany, France, Switzerland, The Netherlands, UK, and Spain). While the coordinating body has had success at arranging cross-nation collaborations and has been a useful forum for minimizing duplication, the national programs continue to be separate and distinct. The European programs have led to advances in new fabrication processes (most notably a synchrotron-based process to produce high-volume, precision metal parts), specialized processing equipment (deep etching equipment and lithographic/exposure tools for bonding) and integrated sensor and signal processing approaches, particularly in biological and chemical sensors and biomedical analytical instruments.

US industry investments in MEMS research, development and production are projected to reach nearly $120 million dollars per year in 1995, with industry investments in the rest of the world estimated at $250 million per year in 1995 [18,21,25]. Portions of the increased investments are being targeted at next-generation MEMS product concepts including higher-functionality sensors and actuator-enabled MEMS for use in: mass data storage (for both conventional magnetic data storage systems and atomic resolution data storage systems), fluid regulation and control (ink-jet printheads, valves, regulators and combustion controllers), and microoptomechanical components (displays, fiber-optic switches, and aligners). Most of the industry investments continue to be focused on transitioning developed concepts to production, improving reliability and production yield, and reducing manufacturing costs.

As these products are commercialized, many of the technology requirements being identified are capabilities that would be beneficial to the industry as a whole, but too costly to develop by any one company. Because MEMS manufacturing is heavily dependent on microelectronics manufacturing and is only a fraction of the size of microelectronics manufacturing, there is currently no MEMS equipment and material suppliers' infrastructure separate from the microelectronics equipment and material suppliers' infrastructure [18, 40, 41]. Cross-cutting, product-neutral investments in MEMS-specific electronic design aids, manufacturing equipment, generic packaging and techniques, and characterization tools that would enhance MEMS manufacturing resources, are not being made by industry, especially in the US. While advanced MEMS device designs, systems concepts and fabrication processes will continue to be important, advances in MEMS manufacturing resources will pace future development, commercialization and use of MEMS.

The DoD Investment Strategy for MEMS

A strong US MEMS technology and manufacturing base is essential to assure early, affordable, and responsive access to MEMS technology for DoD needs. Relatively small investments in MEMS will leverage the vast and historic national investments made in capital equipment, materials, processes and expertise for the microelectronics industry to create a superior, national MEMS capability.

While ongoing industry investments in MEMS will continue to grow, the bulk of these investments are by individual companies focused on gaining incremental improvements in performance and manufacturing costs for their one or two major products. Because DoD will be the early customer for advanced and integrated MEMS devices (ranging from inertial navigation on a chip to advanced maneuverability aircraft), DoD investments will focus on the development of advanced MEMS materials, devices, systems and manufacturing resources and will target the development of supporting capabilities that enable rapid and flexible access to those resources.

The DoD MEMS research and development strategy is to:

- **invest in advanced MEMS devices and systems** leading towards MEMS with higher levels of functional capability, higher levels of integrated electronics, and greater numbers of mechanical components. Activities in this area will accelerate the development of actuator-enabled applications and the shift from discrete MEMS component manufacturing to the manufacturing of integrated MEMS devices. Focused thrusts include the development of new materials, devices, systems, fabrication processes, and interfacing/packaging techniques. Example target devices and applications include navigation-grade inertial guidance systems on a chip, complete hand-held analytical instruments, and distributed aerodynamic control of aircraft;
- **invest in the development of a MEMS infrastructure** by developing support and access technologies including electronic design aids and data bases, shared fabrication services, and test/evaluation capabilities. Infrastructure activities will increase and broaden the pool of MEMS designers, enable rapid, timely and affordable access to MEMS technologies for evolving DoD needs, and create a national mechanism for cost-effective MEMS prototyping and low-volume production. An on-going project supported by the Advanced Research Projects Agency (ARPA) offering regular, shared access to a single, common MEMS fabrication process has already been used by over three hundred users at service/federal laboratories, domestic companies, and universities. More than half the users (and all the small businesses) are getting their first and only access to MEMS technology through the shared fabrication service.
- **invest in activities to accelerate insertion** of presently available or near-term commercial MEMS products into military systems and operations. Examples include munitions safing and arming and condition-based maintenance. Investments in this area are focussed on improved,

affordable manufacturing resources, assembly/packaging techniques, and methods of assessing and qualifying device performance and reliability for DoD applications. Activities in this area encourage and are aligned with industry-formed teams that speed the introduction and use of MEMS fabrication processes and products;

- **coordinate and complement federal programs** within DoD and at other agencies by establishing a DoD and interagency MEMS specialists group, chaired by a representative of ARPA. Examples of ongoing activities in this area include coordinated projects in fluid dynamics and integrated MEMS fluidic devices (AFOSR and ARPA), piezoelectric materials and munitions safing/arming and guidance (ARDEC, ARL, and ARPA), distributed environmental sensors and condition-based maintenance (Marines, NRL, and ARPA), materials standards and databases (NIST and ARPA), and a project to broaden education and training programs in MEMS, increase the number of qualified MEMS instructors, and couple them to shared fabrication services (NSF and ARPA).

DoD funding of MEMS research and development projects over the last three years, primarily at ARPA*, have created a strong US MEMS science and technology base which has demonstrated multiple and varied DoD applications, made accessible commercially-based MEMS manufacturing resources and devices for DoD systems, and sparked a rapid growth in domestic MEMS commercialization activities.

Continued DoD MEMS R&D funding, growing to and sustained at a projected $75 million per year in fiscal 1998, builds on existing accomplishments and capabilities to produce future MEMS devices and processes with the higher functionality and flexibility required to meet present and future DoD needs.

	1995	1996	1997	1998	1999
Devices and Systems	17	24	33	40	40
Support and Access Technologies	5	7	9	10	10
Insertion Activities	3	15	21	25	25
Total	**25**	**46**	**63**	**75**	**75**

TABLE 1. Past and Projected DoD funding profile in MEMS R&D ($M).

Starting in fiscal year 1996, service investments of approximately $3 million for each service growing to roughly $7 million for each service by 1997 will harvest device and systems developments to qualify and adapt MEMS technology for service needs, positioning MEMS devices for procurement and insertion into weapons systems starting in 1998-1999.

*http://eto.sysplan.com/ETO/MEMS/

DoD will also be the early beneficiary and user of an accessible MEMS infrastructure that opens maturing manufacturing resources for high-volume products and makes them available for the production of related, but low-volume DoD products. Continuing cross-company, product-neutral investments in manufacturing resources will increase the level of integrated mechanical components and electronics, expand the range and types of MEMS-specific electronic design aids, manufacturing equipment, generic packaging and interfacing techniques and characterization tools. Finally, focused DoD investments for the assessment, qualification and adaptation of commercially available MEMS technology are accelerating the incorporation of existing and near-term MEMS device capabilities into existing and planned weapons systems.

With a strong MEMS technology base, a growing MEMS manufacturing capability, and coordinated Federal and industry investments, the US can cost-effectively leverage its semiconductor industry leadership into industry leadership in MEMS.

Appendix: MEMS Technology

Using the fabrication processes and materials of microelectronics as a basis, MEMS processes construct both *mechanical* and electrical components. Mechanical components in MEMS, like electronic components in microelectronics, have dimensions that are measured in microns and numbers measured in millions. MEMS is not about any one single application or device, nor is it defined by a single fabrication process or limited to a few materials. More than anything else, MEMS is a fabrication approach that conveys the advantages of miniaturization, multiple components and microelectronics to the design and construction of integrated *electromechanical* systems.

Characteristics of MEMS Fabrication Technologies

Regardless of the specific type of micromachining fabrication process used, all MEMS fabrication approaches share certain key characteristics: *miniaturization*, *multiplicity* and *microelectronics*.

Miniaturization is an important but not the sole characteristic of MEMS. There are many advantages to the performance of electromechanical devices and systems that come from miniaturization. Structures that are relatively small and light lead to devices which have relatively high resonant frequencies. These high resonant frequencies in turn mean higher operating frequencies and bandwidths for sensors and actuators. Thermal time constants, the rate at which structures absorb and release heat, are shorter for smaller, less massive structures. But miniaturization is not the principal driving force for MEMS that it is for microelectronics. Because MEMS devices are by definition interacting with some aspect of the physical world (e.g., pressure, inertia, fluid flows, light), there is a size below which further miniaturization is *detrimental* to device and system operation. For example, reducing the size (and consequently the mass) of an accelerometer makes it harder to detect low-g accelerations. This minimum size is different for different applications, but for most MEMS applications, the size limits are a factor of 3 to 5 larger than the smallest microelectronic device features.

As important as miniaturization, *multiplicity* or the batch fabrication inherent in photolithographic-based MEMS processing, provides two important advantages to electromechanical devices and systems. Multiplicity makes it possible to fabricate 10,000 or a million components as easily, quickly, and at the same time as one component. This advantage of MEMS fabrication is critical for reducing the unit cost of devices and the semiconductor industry has proven the benefits of such economies of scale. The second, equally important advantage enabled by multiplicity is the additional flexibility in the design of massively-parallel, interconnected electromechanical systems.

Rather than designing components, the emphasis can shift to designing the pattern and form of interconnections (interactions or coordinated action) among thousands or millions of components. This approach to design has been standard operating procedure in microelectronic systems design for

nearly three decades. When integrated circuit engineers design and lay out a new circuit, they don't design new components, but instead design the pattern of interconnections among millions of relatively simple and identical components. The diversity and complexity of function in integrated circuits is a direct result of the diversity and complexity of the interconnections and it is the differences in the interconnections that differentiate a microprocessor from a memory. The multiplicity characteristic of MEMS has already been exploited in the development and recent demonstration of a digital micromirror display. In an array about the size of two standard postage stamps, over a million mirrors, each the size of a red blood cell, collectively generate a complete, high-resolution video image. Trying to build and operate such a display using conventional methods of mechanical component manufacturing and assembly would be nearly impossible and certainly not affordable.

Finally, neither the miniaturization nor the multiplicity characteristics of MEMS could be fully exploited were it not for the *microelectronics* that is merged with the electromechanical components. Whether the electronics processing and micromachining steps are interleaved, the electronics processing precedes the micromachining steps, or the microelectronics processing and the micromachining are done separately and later flip-chip or wire-bonded does not matter. The integrated microelectronics provides the intelligence to MEMS and allows both the closed-loop feedback systems, localized signal conditioning, and the control of massively-parallel actuator arrays. Furthermore, the considerable and historic investments in microelectronics materials, processing and expertise will accelerate not only the development of MEMS devices, but will also accelerate the acceptance of MEMS devices by systems designers and integrators.

Fabrication Methods and Materials

Common processing techniques that are used to sculpt mechanical structures include bulk micromachining, wafer-to-wafer bonding, surface micromachining, and high-aspect ratio micromachining. While the objective of all these techniques is the fabrication of integrated mechanical and electrical structures, some techniques are best suited for MEMS with robust mechanical parts and structure, some for high-precision components, and others for high levels of integrated electrical-mechanical components.

Bulk micromachining is the term applied to a variety of etching procedures that selectively remove material, typically with a chemical etchant whose etching properties are dependent on the crystallographic structure of the bulk material. By using appropriate material coatings and patterning steps to mask the surface of the material (most commonly silicon wafers of the same type used in microelectronics fabrication, but quartz wafers are also used), selective areas of the wafer surface can be exposed to the micromachining etchants. The shape of the etched cavities and etch rates are typically determined by the crystalline structure of the wafer material and the particular etching reaction (a type of etching termed anisotropic etching).

Additional variations in the type of features and structures are possible by selective and patterned doping (the injection of other atoms, such as boron, up to twenty microns into the pure-silicon surface) of the wafer. Doping inhibits the action of the crystalline etches and thus can leave behind free-form structures following a bulk, anisotropic etching of material. Figure 17 is an illustration of an example component with a composite of all common features and mechanical structures that can be etched in single-crystal silicon using bulk micromachining. The features and structures range from pyramidal pits and v-groove trenches to membranes and cantilevered beams. The cantilevered beam (the “diving board”) and doubly-supported beam (the bridge) suspended above the etched v-groove in Figure 17 would have been defined by rectangular doping patterns (corresponding to the beam geometries) prior to the etch of the v-groove. Bulk micromachining is an extensively used commercial process, particularly in the production of pressure sensors, accelerometers, and flow regulators.

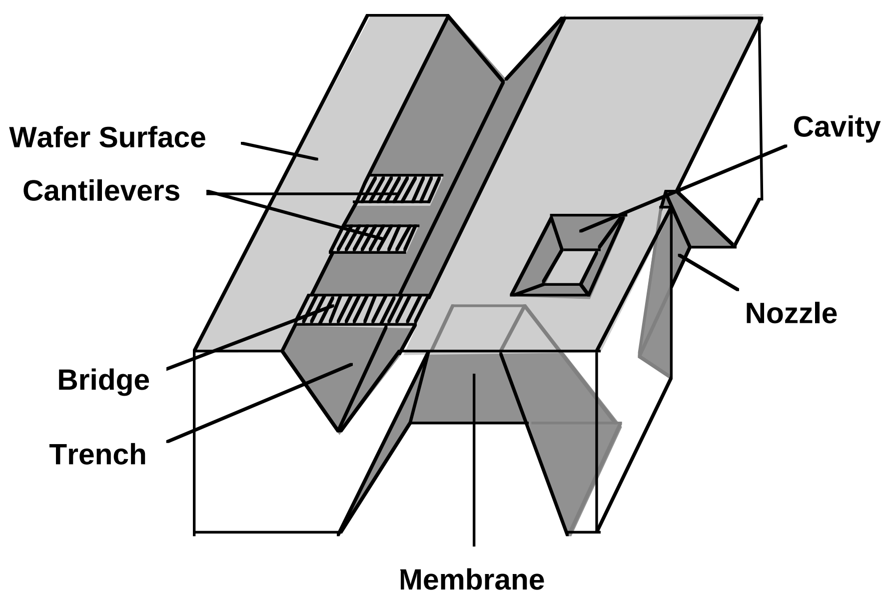


FIGURE 17. An arbitrary component with a composite of all common features and mechanical structures that can be etched in a piece of single-crystal silicon using bulk micromachining. Note that all etched walls are at the same angle as defined by the crystal orientation of the silicon (adapted from Mechanical Engineering [20]).

Wafer-to-wafer bonding is a strategy commonly employed to get around the restrictions in the type of structures that can be fabricated using bulk micromachining. Because anisotropic etching, by definition, only *removes* material, bonding of wafers allows for the *addition* of material to the bulk micromachining repertoire. Wafer-to-wafer bonding is the bonding (under

pressure or a combination of pressure and a high voltage across the wafer) of two or more micromachined wafers to construct MEMS. Constituent wafers can be bulk micromachined wafers, wafers with prefabricated electronics, or wafers micromachined by other techniques. In many cases, the bonded wafers are silicon-to-silicon, but silicon-to-quartz and silicon-to-pyrex bonds are also common. Wafer-to-wafer bonding is a versatile fabrication technique suitable for processing whole wafers at a time (a wafer-scale technique that maintains the advantages of batch fabricated processes) and yields high-quality interfaces and bonds. Heavy commercial use of wafer-to-wafer bonding is made in the production of pressure sensors and integrated fluidic systems (flow valves and regulators, ink-jet nozzles, pumps, chemical sensors, and miniature analytical instruments).

Despite the usefulness of bulk micromachining and wafer-to-wafer bonding (and their continuing commercial importance), these micromachining techniques are limiting in the type of features that can be sculpted. Bulk micromachined structures and features are defined by the internal crystalline structure of the material. Fabricating multiple, interconnected electromechanical parts of free-form geometry using bulk micromachining is often difficult or impossible. While wafer-to-wafer bonding gets around some of these limitations, truly free-form geometries and integrated multi-component (multiple, interconnected and co-fabricated components) electromechanical structures are presently produced by a relatively new micromachining approach that is fundamentally different from bulk micromachining and wafer-to-wafer bonding.

Surface micromachining, like bulk micromachining, also starts with a wafer of material. But unlike bulk micromachining where the wafer itself serves as the stock from which material is removed to define mechanical structures, in surface micromachining the wafer is the substrate--the working surface--on which multiple, alternating layers of structural and sacrificial material are deposited and etched (Figure 18). A typical cycle in a surface micromachining process begins with a deposition of either the sacrificial material (a material which will be completely removed in the final step of the fabrication process) or the structural material (a material from which the functional components of the electromechanical system will be constructed). The layer is then masked with a desired pattern which is typically transferred using a photolithographic process, usually the exposure of a photosensitive material (photoresist) and development (removal) of the exposed photoresist. Next, the underlying material not protected by the masking pattern is etched, typically by reactive ion etching (a sort of sand blasting with ions) to transfer the mask pattern to that particular material layer. The deposition-masking-etching cycle is repeated on all the laminated layers of structural and sacrificial materials until the MEMS device structure is complete. The final step in surface micromachining is the release of the structural material from the laminations by etching or removing the underlying and surrounding sacrificial materials.

The most commonly used surface micromachining processes start with silicon wafers of the same grade and type used in microelectronics fabrication

and uses layers of silicon dioxide as the sacrificial material and layers of polysilicon (a deposited, less crystalline form of silicon) as the structural material. Other deposited materials such as silicon nitride, polyimides, and aluminum are also extensively used to provide electrically insulating materials, conducting materials, etchant masks, and additional structural materials. All of these materials are extensively available and used in standard microelectronics fabrication.

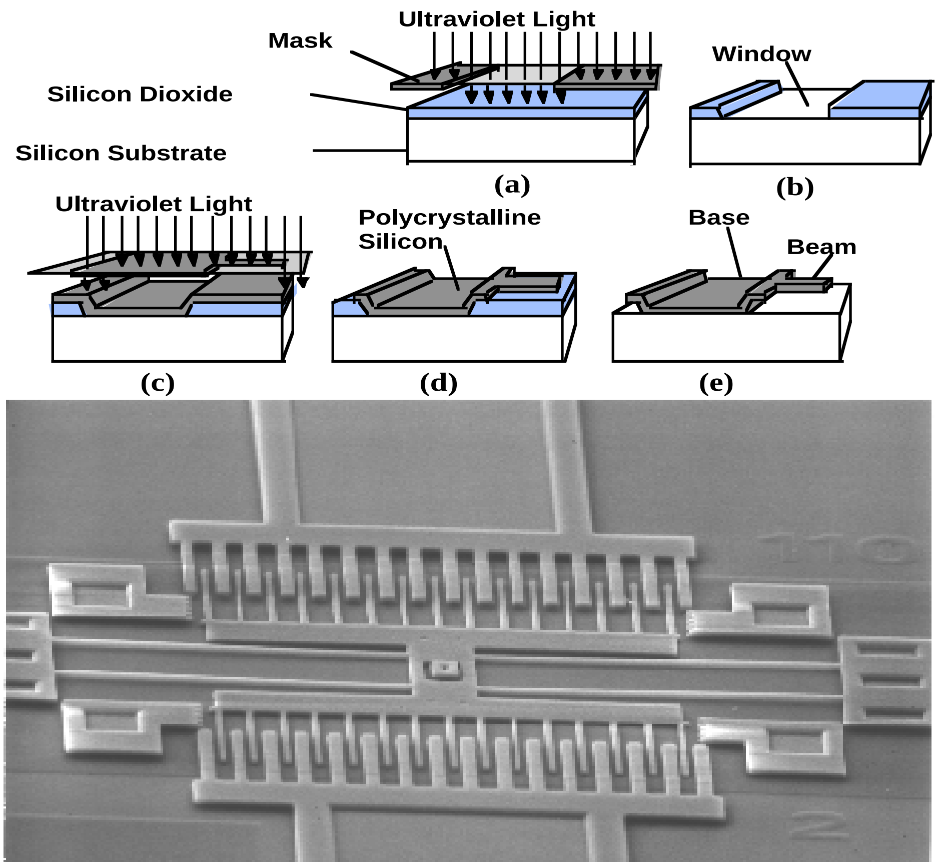


FIGURE 18. A single cycle in a common surface micromachining process. The process to build a single cantilever beam begins with the sacrificial material layer (silicon dioxide) being patterned and etched (a, b). Next, the structural material (polysilicon) is deposited over the entire surface. The polysilicon is then patterned and etched in the shape of the cantilever beam and base (c, d). Finally, the polysilicon is released by removing the remaining and underlying silicon dioxide (e). A portion of the patterned polysilicon is attached to the substrate forming the base (where the silicon dioxide was removed) and portions are suspended above the substrate and free to move (where the silicon dioxide had remained). The scanning electron microscope picture is a side-view of a comb-drive resonator fabricated with such a sequence. Note the two tri-indented square anchors that are the base holding the rest of the central folded beam and comb structures suspended above the substrate [19].

Because of the laminated structural and sacrificial material layers and the etching of material done by a process that is insensitive to crystalline structure (either because of the etch or because the material itself is non-crystalline), surface micromachining enables the fabrication of free-form, complex and multi-component integrated electromechanical structures, liberating the MEMS designer to envision and build devices and systems that are impossible to realize with bulk or bonded processes. Surface micromachining also frees the process developer and device designer to choose any material system that has complementary structural and sacrificial materials (structural materials that are unaffected by the etching of the sacrificial material). Examples of other material pairs include metals as structural materials paired with polyimides as sacrificial materials.

It is this freedom to fabricate devices and systems without constraints on materials, geometries, assembly and interconnections that is the source for the richness and depth of MEMS applications that cut across so many areas. *More than any other factor, it is surface micromachining that has ignited and is at the heart of the current scientific and commercial activity in MEMS*.

High-aspect ratio micromachining is an even newer machining technique, developed (originally in Germany) to allow the fabrication of thick (usually greater than hundreds of microns and up to centimeters thick), precision, high-aspect ratio MEMS structures (structures with near-vertical sides). Bulk micromachined structures are typically limited to thicknesses of a few hundred microns. Surface micromachined structures, with their deposited structural films are much thinner, usually limited to thicknesses of no more than five to ten microns. Like all the other micromachining techniques reviewed so far, high-aspect ratio micromachining uses photolithographic processes, but the photoresists layers are hundreds of microns to centimeters thick rather than the one to two microns typical in bulk and surface micromachining. Furthermore, the exposure source for the photoresist is a synchrotron (X-rays) rather than the standard and more easily available ultra-violet and deep ultra-violet sources used in semiconductor fabrication. High-aspect ratio micromachining begins with the exposure and development of the thick photoresist which leaves deep, high-aspect ratio “canyons” in the photoresist. Next electroplating is used to fill the canyons with metal (typically nickel, but any metal that can be electroplated will do) that will mold itself into the shape of the patterned canyons. Following the plating step, all photoresist is removed leaving behind metal parts with geometries defined by the thickness of the original resist layer and the sub-micron precision exposure of X-rays.

At present, high-aspect ratio micromachining is not yet a commonly used or available MEMS fabrication process. It is especially useful in the construction of electromagnetic MEMS (because of the relatively large structures and high-permeability metals that can be electroplated) and also holds promise as an end-run technology to produce high-volume, low-cost, precision piece parts without conventional milling and machining tools.

End-Stage Fabrication Steps

Major differences also arise during the processing steps at the end of the manufacturing cycle (end-stage fabrication) for MEMS devices compared with purely microelectronic devices. The principle difference, and the root cause of all subsequent processing differences, is the release of the mechanical structures.

In the case of surface micromachined MEMS, the release requires new techniques and equipment. The sacrificial material to be removed is typically one to two microns thick and is sometimes underneath structures that are hundreds of microns in cross-sectional area. If the sacrificial material is removed using a wet etch (typically with hydrofluoric acid in the most common, polysilicon/silicon dioxide material pair), the subsequent rinsing and drying of the wafer to remove the acid is very critical to the yield of functional MEMS devices. A casual rinsing and drying of the etched wafer usually leaves most of the mechanical structures stuck to the substrate rather than suspended above the substrate as intended. The extent of sticking and hence the ultimate yield depends on many factors including the specific geometries of the mechanical devices (smaller, stiffer structures are less likely to stick than larger, more flexible structures) and the surface properties of the materials involved (are the structures hydrophilic or hydrophobic, do they retain electrostatic charges or not).

A number of new techniques have been developed to reduce the forces causing sticking of mechanical parts. Some of the more successful techniques have employed sublimation and supercritical drying. Sublimation techniques keep the wafer submerged under liquid throughout the etching and rinse procedure. After the liquid solution has been blended from the acid to the final rinse compound, a thin layer of the solution covering the wafer is frozen solid (either by cooling the wafer or by using a rinse compound with a melting point above room temperature). The wafer, with the now solid layer of rinse solution, is then placed in a vacuum and the rinse compound sublimates (evaporates from the solid form directly without going through a liquid phase). Supercritical rinse techniques use special rinses (like carbon dioxide and even water) at high pressures and temperatures to effect the same function.

Assuming a high-yield, wafer-scale release of the mechanical parts (from either bulk, surface or high-aspect ratio machining), the wafer now has to be diced up and sectioned into the individual MEMS chips or dies. For wafers with purely microelectronic devices, this is typically done with a sawing step. A circular-saw with diamond-embedded blades is used to cut out the usually rectangular devices in a series of regular and cross-hatched cuts. Because the blade generates heat as it cuts through the wafer, it has to be cooled with a continuous stream of water directed at the blade-wafer contact area throughout the sectioning process. This generates a slurry of water and fine grit which covers the entire surface of the wafer. For a wafer of microelectronics, with no suspended parts or gaps, the slurry poses no problems. For MEMS the slurry is disastrous. Steps have to be taken to protect the

released parts during the sectioning without damaging the parts or requiring a re-release of the parts (negating the economic advantages of batch fabrication).

Even after a successful release and sectioning, the individual dies now have to be handled and assembled into a package. The handling and packaging of the MEMS dies has to be accomplished without damaging the mechanical structures or altering their properties (for example, introducing stresses in the die that alter resonant frequencies beyond designed targets). Furthermore, unlike microelectronics packaging, the objective in MEMS packaging is not to completely seal the device from the environment. The whole point of the MEMS device is to interact with the physical world, whether it is to sense or act. MEMS will require new approaches to packaging (which should more properly be termed interfacing) that will selectively seal and expose different parts of MEMS devices to their environments. Because each MEMS application area involves different physical forces and interactions, the different applications will require unique solutions that are unlikely to be similar to already solved problems from other MEMS applications. MEMS fluidic devices, like ink-jets and pumps, present a completely different set of interfacing requirements (packages must allow contact with fluids but seal other portions) as compared to a MEMS optical system (package must be transparent to wavelengths of interest but must maintain a vacuum).

Design and Simulation Tools

MEMS is more demanding of electronic design aids than microelectronics is. MEMS requires new drawing and layout tools to generate the patterns that will be used to add or remove material during processing. In addition, MEMS requires not only a number of different modelling tools including simulators for mechanical deformation, electrostatic fields, mechanical forces, electromagnetic fields, material properties, and electronic device simulators, but MEMS also needs the connective algorithms to reconcile and blend results from all the different simulators.

As a simple example of the need for different and connected simulators, consider a single cantilever beam (diving board) suspended above the substrate at some initial gap, holding an electric charge. An electric field simulator calculates the force due to the field created by the charge, which is then fed to the mechanical deformation simulator. The mechanical deformation simulator determines the bending of the beam due to the force and calculates a new gap. Because the gap changed, the electric fields will now be different and must be recalculated to reflect the new mechanical position of the beam. The new fields will cause new forces which will in turn cause further deformations in the mechanical structures, causing yet further changes in the field and so on. The transfer back and forth of the device simulation results among the different simulators is repeated until a stable solution is reached. For simple MEMS devices, like a cantilever, and one or two simulators, a stable solution is reasonably assured and simple to calculate. As devices

become more complex (thousands of independent mechanical elements) and multiple simulators are involved (for example fluid and temperature models), the complexity of both the simulations and the coupling grow exponentially and results do not typically reach closure. Radically new approaches to modeling and simulation for the many physical effects and different functions of MEMS will need to be developed.

Many of the new material property simulators will also need new models and data to relate process parameters to material properties relevant for MEMS design. Simulators and models are only as good as the data they are built on. The accuracy of the existing microelectronic device simulators is built on historic and huge amounts of material and device measurements coupled to carefully controlled process conditions. By knowing the relationship between processing conditions and the resulting material parameters, people who manufacture microelectronics can control material properties, and hence, device yields. Understandably, microelectronic circuit designers were interested in properties that related to the electronic function of the devices they were building--like doping levels and dielectric constants. There are very few reliable measurements of material properties (for example, modulus, residual stress, or reflectivity) relevant to the production of MEMS. As more material data and related models for MEMS devices become available, the accuracy of simulators will increase as will the rate of successful, first-pass MEMS designs.

New drawing and pattern layout tools to take into account the free-form geometries of MEMS designs and systems are also needed. All of the tools used to make the masks for transferring the pattern of material deposition or etching were developed for the manufacture of microelectronic circuits. As such, they were developed with the ability to draw rectangular features (adequate for defining the electrical properties of the device) in square grids (commonly referred to as Manhattan geometries). Just as important as the layout tools and more difficult to build are related design rule checkers. Analogous to spell-checkers in word processing applications, design-rule checkers are an automated way to detect violations of constraints imposed by the fabrication process. For example, the release step may require that structures with cross-sectional areas greater than some threshold need to have etch holes at periodic intervals to facilitate the etching of the underlying sacrificial material. If the MEMS designer were to layout a structure with area greater than this threshold, the design rule checker would alert the designer to the situation. Obviously, different processes would have different designs constraints, requiring different and associated design rule checkers (just as a French word processor would require a different spell-checker from the spell-checker for an English word processor). Finally, as in the case with design simulators, the additional functionality of MEMS creates needs not encountered in microelectronics such as automated ways to detect designs without sufficient clearance for mechanical structures to move or designs that result in released mechanisms that will collide.

Comparison of MEMS and Microelectronics Technologies

Although MEMS fabrication uses many of the materials and processes of semiconductor fabrication, there are important distinctions between the two technologies. The most significant distinctions between MEMS fabrication and semiconductor fabrication are in the process recipes (the number, sequence and type of deposition, removal and patterning steps used to fabricate devices) and in the end-stages of production (bonding of wafers, freeing of parts designed to move, packaging, and test). The fundamental challenge of using semiconductor processes for MEMS fabrication is not in the type of processes and materials used but more in the way those processes and materials are used (Figure 19).

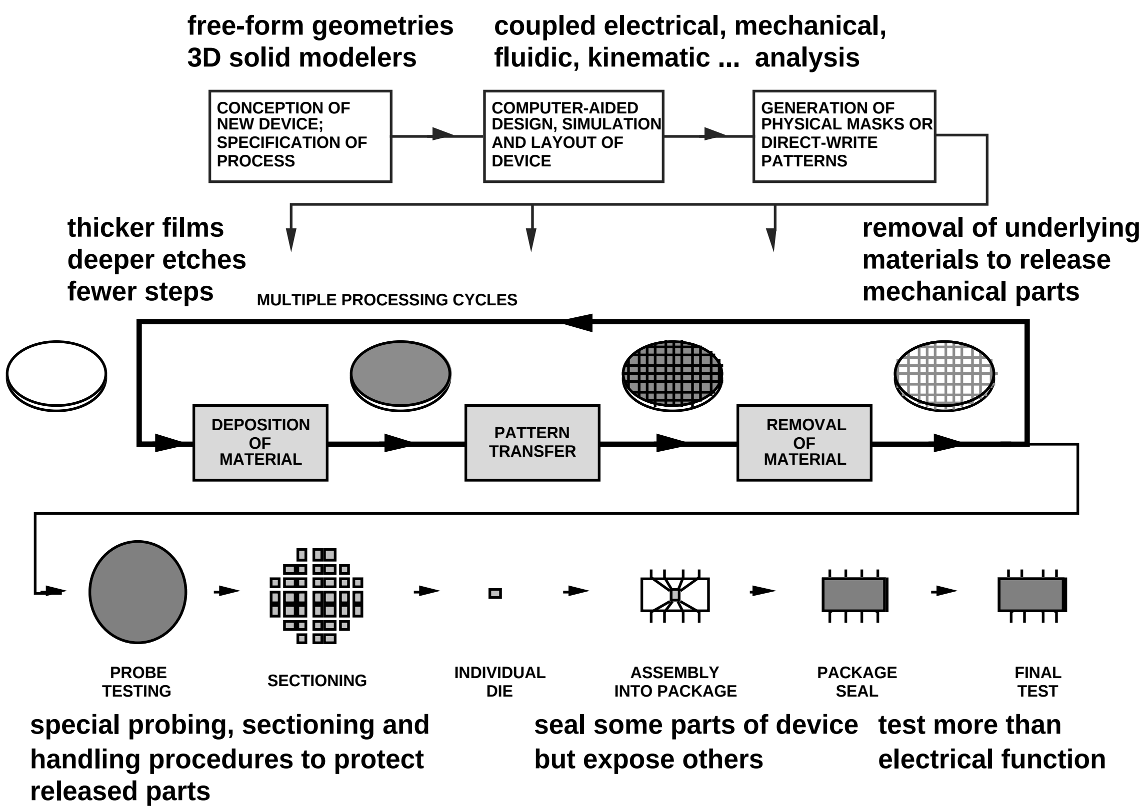


FIGURE 19. The manufacturing process flow for a typical microelectronic integrated circuit and a MEMS device. The first phase of the process includes process specification, device design and mask layout. This is followed by device fabrication, typically multiple slices of material deposition and patterned removal of material. Finally, wafers are probed, partitioned into individual devices, packaged and tested. Despite distinctions in film thicknesses, etch depths, and the release of mechanical structures, the two technologies use the same equipment and materials in the central deposition- photolithography-etch cycles. The significant distinctions between MEMS and electronics processing arise in the electronic design aids and simulators, and in the sectioning, packaging and testing. Examples of these distinctions are shown in italicized, bold text.

Surface micromachining, the MEMS fabrication technology that uses the most standard microelectronics fabrication processes and materials is also the one that uses those processes and materials at their extremes. First, the films typically deposited for MEMS are thicker than the films deposited for microelectronics. Whereas microelectronic films are usually in the range of 100s to 1000s of angstroms, MEMS films are usually in the range of 1000s to tens of thousands of angstroms. Second, as a direct consequence of the thicker films, the material removal steps or etches (typically plasma and reactive ion etches, often referred to as “dry” etching as opposed to “wet” chemical etching) are necessarily deeper and take longer. Consequently, the etch profiles (the shape of the sidewalls in the etched features) become harder to control and maintain to target specification--most often due to undercutting of the etch. Third, the successive buildup of material from multiple depositions, patterning and etching of material makes the surface of MEMS-processed wafers very non-planar after only a few process cycles. This presents difficulties both for later photolithographic steps (features on prominences in the wafer will be out of focus if features in the depressions are in focus) and later material depositions (thinned areas and even breaks in the surface coverage may occur, particularly at sharp transitions from prominence to depression). Finally, a processing step unique to MEMS is to free or release the parts designed to move (membranes, resonating beams, tiltable mirrors) by removing material underneath portions of these parts. The release of the movable and structural components presents additional considerations for MEMS that are never encountered in microelectronics processing. One important consideration is residual stress inherent in the released films as a result of deposition. If not properly controlled the stresses will cause the released, mechanical structures to bow and bend, lose their designed shape and orientation and destroy the functionality of the MEMS devices.

The differences between MEMS and microelectronics process steps illustrate that while MEMS fabrication uses available semiconductor fabrication equipment and processes, the equipment and processes are used in non-standard ways, often at the extremes of the operating conditions for which they were designed. MEMS will need the development of operating conditions on standard semiconductor equipment suited and optimized to the requirements of MEMS. For other processing steps unique to MEMS, the development of new manufacturing equipment and associated processes will be required.

Only as MEMS are being commercialized and manufacturing realities are identifying production requirements, are we now in a position to begin investments in electronic design aids, MEMS-specific manufacturing equipment, and packaging/interfacing techniques. While advanced MEMS device designs, systems concepts and fabrication processes will continue to be important, increasingly it is advances in these MEMS-specific manufacturing resources that will pace the developments, commercialization and use of MEMS.

Trends in MEMS Technology

By merging the capabilities of sensors and actuators with information systems, MEMS is extending and increasing the ability to both perceive and control the physical world. In order to quantitatively measure and track this ability and compare MEMS developments across diverse application areas, Figure 20 illustrates a map of electromechanical integration. The ordinate is a log plot of the number of transistors ranging from one to one billion. Similarly, the abscissa is a log plot of the number of mechanical components ranging from one to one billion. To first order, the number of transistors are a measure of information processing ability and the number of mechanical components are a measure of perception and control ability.

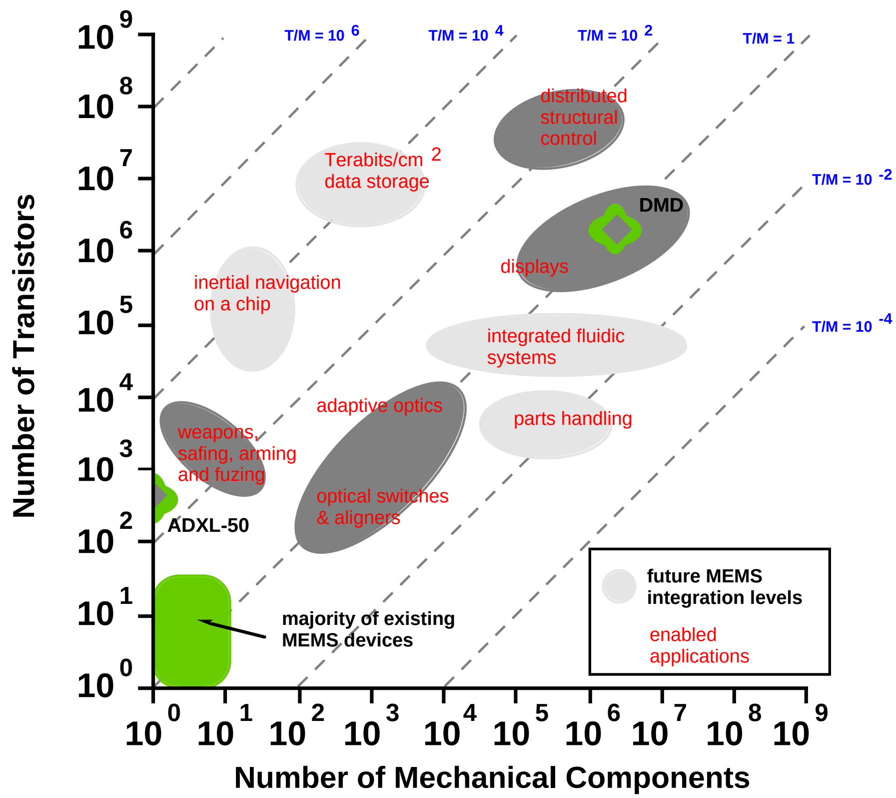


FIGURE 20. Log-log plot of number of transistors merged with number of mechanical components for MEMS devices and systems. Contours of equal transistors-to-mechanical-components ratios (T/M) are lines of 45° slope. Lines representing T/M ratios ranging from 10^{-4} to 10^{6} are shown for reference. The resulting map represents a quantitative way to measure and track MEMS technology advances across different application areas [50].

Plotted on this graph is the region containing the ratios for many historic and current MEMS devices, ratios for some recent advanced MEMS devices,

and regions of ratios required for future MEMS technologies and applications.

As can be seen from Figure 20, the region containing many current MEMS devices (e.g., pressure sensors, accelerometers, and the flow valve described earlier) is a small area near the lower left of the plot, or the region representing devices with a few mechanical components and a ratio of one to a few transistors per mechanical component. Moving out from this cluster near the origin, regions of higher levels of integrated electronics are generally to the left and top, and regions of greater numbers of mechanical components are to the right and top. Recent MEMS technology advances have made possible two MEMS devices of higher integration levels and greater number of integrated mechanical components, each developed for completely different applications. These devices are also plotted on this graph. One is the ADXL-50, a MEMS accelerometer with approximately 200 transistors to a single mechanical proof mass [9] and the other is the digital micromirror display (DMD) with approximately six million transistors to two million mechanical micromirrors [44].

In different ways, both these devices represent significant advances for MEMS technology and MEMS devices capabilities. The ADXL-50 has moved up from the current MEMS region onto a higher integrated electronics to mechanics line (T/M $\approx$ 200), but has kept the number of mechanical components at one. In contrast, the DMD has stayed on nearly the same processing to perception and control ratio line (T/M $\approx$ 6), but has increased the number of both transistors and mechanical components (because of the replicative, identical mirrors and underlying electronics inherent in the structure of the device) by nearly six orders of magnitude.

The higher levels of integrated electronics and the greater number of integrated mechanical components represented by these two MEMS devices quantify the degree of recent MEMS technology advancements. In the context of the entire graph, the two points also illustrate the opportunity in MEMS represented by the regions of processing, perception and actuation integration yet to be explored. These unexplored regions are not only guides for advances in integration, but are also a guide to the capabilities that will be enabled at those integration levels. For example, to develop inertial navigation units on a chip will likely require nearly two orders of magnitude increase in both the number of transistors and mechanical components to reach the sensitivity and stability necessary in those devices. In contrast, the development of some fluid pumps or microoptomechanical devices will likely require greater numbers of mechanical components, but at lower levels of integrated electronics than other MEMS applications.

Future MEMS applications will be driven by processes that enable greater functionality through higher levels of electronic-mechanical integration and greater number of mechanical components. These process developments in turn will be paced by investments in the development of new materials, device and systems design, fabrication techniques, packaging/assembly methods, and test and characterization tools.

Reference List

(1) 39th Annual Fuze Conference, American Defense Preparedness Association. April 26 and 27, 1995.

(2) "ADI Accelerates Opportunities for MEMS and Micromachined Sensors." *Sensor Business Digest,* October, 1994.

(3) *AMCCOM Final Report on CMS and Operation Desert Sweep,* (DRAFT) CMS, Inc. 1992.

(4) Bryzek, Janusz; Peterson, Kurt; McCulley, Wendell. "Micromachines on the March." *IEEE Spectrum*, May 1994.

(5) *Building U.S. Capabilities in Flat Panel Displays*, U.S. Department of Defense, October 1994.

(6) Burgess, Lisa and Munro, Neil. "Microscopic Warriors, Weapons May Reshape War." *Defense News,* February 21, 1994

(7) Browne, Malcolm W. "Micro-Machines Help Solve Intractable Problem of Turbulence." *New York Times*, January 3, 1995.

(8) *Conventional Weapons Detailed Technology Area Plan - Draft*, U.S. Department of Defense, 1994.

(9) Core, Thomas A; Tsang, W.K.; and Sherman, Steven J. "Fabrication Technology for an Integrated Surface-Micromachined Sensor." *Solid State Technology,* October 1993.

(10) Coy, Peter; Carey, John; and Gross, Neil. "Mighty Mites Hit it Big." *Business Week*, April 26, 1993.

(11) Dahmen, David. *Semiconductors: Developing the Electronics Industry.* A World Bank Symposium, 1993.

(12) Druffner, Richard A. and Lewis, Raymond J. "Embedded Training Offers Savings, Improved Learning." *Signal*, July 1993.

(13) *Foreign Electronics Technology Assessment - Draft*, National Science and Technology Council; Electronics Subcommittee, December 1994.

(14) Fulghum, David A. "GDAM Errors to be Slashed." *Aviation Week and Space Technology,* February 27, 1995.

(15) Fujita, H. and Gabriel, K.J., "Future Directions in Microactuators", Plenary Paper, *Transducers'91, IEEE Solid-State Sensors and Actuators Workshop*, San Francisco, 1991.

(16) *FY95 Conventional Armament Technology Area Plan,* Directorate of Science and Technology, Wright-Patterson AFB, OH.

(17) *FY95 Joint Service Program Plan*, Joint Directors of Laboratories, U.S. Department of Defense, 1994.

(18) Gabriel, Jurgen and Gessner, Wolfgang. “Government Promotion of Microsystems Technology in Europe.” *International Working Papers No.1*, VDI/VDE Technologiezentrum Informationstechnik GmbH, October 1992.

(19) Gabriel, Kaigham, “Microelectromechanical Systems Program: Summary of Research Activities.” Advanced Research Projects Agency, July 1994.

(20) Howe, R.T., et al., “Micromotor on a Chip”, *IEEE Spectrum*, July 1990.

(21) *JTEC Panel Report on Microelectromechanical Systems in Japan*. Japanese Technology Evaluation Center, September 1994.

(22) Kaplan, Karen. “Device Looks Like a Chip, Works Like a Robot--and Fits on a Fingertip.” *Los Angeles Times,* February 22, 1995.

(23) Kimmel, Cary. “Trends in Worldwide Sourcing in the Electronics Industry.” in *Developing the Electronics Industry*, A World Bank Symposium, 1993.

(24) Mehregany, Mehran. “Introduction to Microelectromechanical Systems and the Multiuser MEMS Processes Activities.” *Case Western Reserve University/MCNC Short Course Handbook*, 1993.

(25) *Microelectromechanical Systems Market Study*, System Planning Corporation. July 1994.

(26) *Microelectromechanical Systems Military Applications*, System Planning Corporation, December 1994.

(27) *Micro-Electromechanical Systems User/Supplier Workshop*, Semiconductor Equipment Materials International, November 1994.

(28) Morrocco, John D. “TGM Strategy Faces Budget, Technical Trap.” *Aviation Week and Space Technology,* February 27, 1995.

(29) National Electronics Manufacturing Framework Committee. *Electronics Manufacturing Technology Roadmaps--and--Options for Government Action,* American Electronics Association, Electronic Industries Association, 1994.

(30) *The National Technology Roadmap for Semiconductors,* Semiconductor Industry Association, 1994.

(31) “Domestic and European RD&T Policies.” MST '91, Berlin, 1991.

(32) Santo, Brian. “U.S., Japan Gear Up For Micromachines.” *Electronics Engineering Times*, November 23, 1993.

(33) Scott, William B. “Micro-Machines Hold Promise for Aerospace.” *Aviation Week and Space Technology*, March 1, 1993.

(34) Stix, Gary. “Micro Machinations.” *Scientific American*, November 1992.

(35) ________. “Toward ‘Point One’.” Scientific American, February, 1995.

(36) *U.S. Industrial Outlook 1994*, U.S. Department of Commerce, 1994.

(37) Thomson, Ralph J. “The U.S. Electronics Industry.” in *Developing the Electronics Industry*, A World Bank Symposium, 1993.

(38) *U.S. Army Fuze Plan,* Picatinny Arsenal, 1994.

(39) Walsh, Edward J. “NAVSEA Seeks Technology Gains for Fire Support Role.” *SEA Power*, October 1994.

(40) MEMS Industry Study Team, March 1994 Meeting, Chicago.

(41) MEMS Small Business Roundtable, San Francisco, January 1995.

(42) European Roundtable on Microsystems, Geneva, Switzerland, 1995.

(43) Wright, LTC Gary W. *Scatterable Munitions = Unexploded Ordnance (UXO) = Fratricide*, US Army War College, Carlisle Barracks, PA. March 22, 1993.

(44) Younse, Jack M. “Mirrors on a Chip.” *IEEE Spectrum,* November 1993.

(45) *Integrated Micro Motion Systems*, Third Toyota Conference, Nissin Aichi, Japan, October 22-25, 1989.

(46) Technical Digest, *Transducers’91, IEEE Solid-State Sensors and Actuators Workshop*, San Francisco, 1991.

(47) Technical Digest, *Transducers’93, IEEE Solid-State Sensors and Actuators Workshop*, Yokohama, Japan, 1993.

(48) Technical Digest, *Hilton Head Solid-State Sensors and Actuators Workshop,* 1992 & 1994.

(49) National Short Course on Fuzing, Corpus Christi, Texas, 1988.

(50) Gabriel, Kaigham. “Engineering Microscopic Machines.” *Scientific American*, September 1995.